Synchrotron Facilities: Meeting Stringent Deformation and Vibration Criteria

Jost A. Studer
Studer Engineering, Zürich, Switzerland

Rocco Panduri
Studer Engineering, Zürich, Switzerland

Hans-Peter Höltschi
Höltschi & Schurter AG, Zürich, Switzerland

6th International Conference on
Case Histories in Geotechnical Engineering, Arlington, VA, August 11-16, 2008

SYNCHROTRON FACILITIES: MEETING STRINGENT DEFORMATION AND VIBRATION CRITERIA

Jost A. Studer
Studer Engineering
Zürich, Switzerland

Rocco Panduri
Studer Engineering
Zürich, Switzerland

Hans-Peter Höltschi
Höltschi & Schurter AG
Zürich, Switzerland

ABSTRACT

Synchrotron light source facilities have high demands on admissible deformations and vibrations of the foundation structure during operation. These research facilities are very complex, consisting of pumps, air conditioning equipments, emergency power generators and electrical transformers of several sizes and types. Such equipments are located on the experimental platform itself or in the vicinity of the platform. On the experimental platform, which is usually a ring with a diameter of 100 to 200 m, typical admissible values for the absolute deformations due to static loads (of 500 kg) and dynamic loads (of 100 kg) are in the range of 1 micrometer, while the admissible vibration amplitudes are in the range of 0.4 to 4 micrometers in the frequency bandwidth of 0.05 Hz to 100 Hz. These values are 500 times smaller than the value perceptible by humans. Moreover, the maximum acceptable values for differential displacements along the experimental platform are typically of 0.25 mm / 10 m / year. All these conditions are decisive for the required accuracy of the needed investigations.

This paper presents case studies of the design of the experimental platforms for two synchrotron facilities, one located in Switzerland and the other in Spain, with extremely different foundation and environmental conditions: While one facility is founded on sound terrace gravel, the other is founded on mudstones with potential shrinking and swelling characteristics. The facilities and the soil conditions at the two sites are briefly discussed, and potential solutions are presented. Different alternatives for the foundation of the experimental platform are presented and compared to each other, also considering economical aspects. The main problem is that the best solutions to meet the vibration criteria are not compatible with the best ones suitable to meet the settlement criteria. The principal features in the feasibility phase and in the later design and execution phase are presented and discussed. The final solutions and their degree of fulfillment will be presented together with lessons learned for future projects.

INTRODUCTION

Synchrotron light is used for the study of microscopic characteristics of materials, providing an insight into different research areas. The synchrotron light is bundled electromagnetic radiation, sharply focused like a laser beam, emitted by electrons with an extreme high velocity. An effective synchrotron light source is composed of numerous magnets forming a storage ring forcing the flying electrons into a circular orbit, and within which the electrons can circulate. The emission of the electromagnetic radiation by the electrons is their reaction to the magnetic force.

Synchrotron light facilities must be capable of producing beams of exceptional brightness and stability. The demands on admissible deformations and vibrations on the foundation slab are therefore very stringent. Given the dimensions of the facility, the subsoil conditions and the vibrations produced in the vicinity play a major role for the fulfillment of these criteria.

DESIGN REQUIREMENTS

The design specifications are mainly determined by the serviceability of the synchrotron light. Tables 1 and 2 show the requirements at Swiss Light Source at the Paul Scherrer Institute in Switzerland (SLS/PSI) and at the ALBA site in Barcelona, Spain, which is in construction for the time being and which will be operated by the Consortium for the Exploitation of the Synchrotron Light Laboratory (CELLS).

The loads on the foundation (based on the required life load) are small, compared to the capacity of the foundation materials.

Table 1. Main deformation criteria at SLS/PSI and ALBA sites for the experimental slab

Description	Values and Criteria	
	SLS/PSI site	ALBA site
Criteria for differential displacements:		
Maximum rates over 10m	0.1mm/year	0.25mm/year 0.05mm/month 10μm/day 1μm/hour
Maximum over perimeter	-	2.5mm/year
Criteria for maximum slab deformations:		
Static load of 500kg (on application point)	-	6 μm
Static load of 500kg (at 2m distance)	-	1 μm
Dynamic load of 100kg	-	1 μm

Table 2. Main vibration criteria at SLS/PSI and ALBA sites for the experimental slab

Values and Criteria	
SLS/PSI site	ALBA site
Total amplitude (vector), frequencies 1-50 Hz: 0.5 μm RMS	Vertical amplitude, frequencies 0.05-1 Hz: 4 μm
The total vibration amplitude of all internal equipment must not exceed 0.2 μm RMS	Vertical amplitude, frequencies 1-100 Hz: 0.4 μm
	Horizontal amplitude: 2 μm

Based on intensive discussions with the operation personnel of the synchrotron facilities, it resulted that the deformation requirements are less stringent than the vibration criteria. While in case of excessive vibrations the operation quality is seriously disturbed, an exceedance of the deformation criteria leads to additional maintenance costs due to the need of periodical adjustments, but does not seriously influence individual experiments. The main problem of the vibration criteria is that they are defined by the amplitude of the vibration displacement, which means that long period vibrations is the controlling factor.

SHORT DESCRIPTION OF CONSIDERED FACILITIES

Swiss Light Source at Paul Scherrer Institut (SLS/PSI)

A major information source on the SLS/PSI is the corresponding web page at http://sls.web.psi.ch.

The SLS/PSI accelerator facility consists of three major parts: a linear accelerator ("linac") which pre-accelerates the electrons, a booster synchrotron which accelerates the electrons coming from the linear accelerator, and a storage ring into which the electrons are injected from the booster. In the storage ring these high energy electrons circulate for hours, generating the desired synchrotron light, which in turn is used in several beam line facilities. Storage ring and booster are housed in a tunnel with concrete shielding walls. Two layers of 40 cm thick concrete beams cover the tunnel and can be removed to give a crane access to the accelerator components. The linear accelerator is located in a separate tunnel. A part of the facility layout as well as a section through the booster and storage ring tunnel is shown in Fig. 1. The SLS/PSI storage ring has a diameter of about 90m.

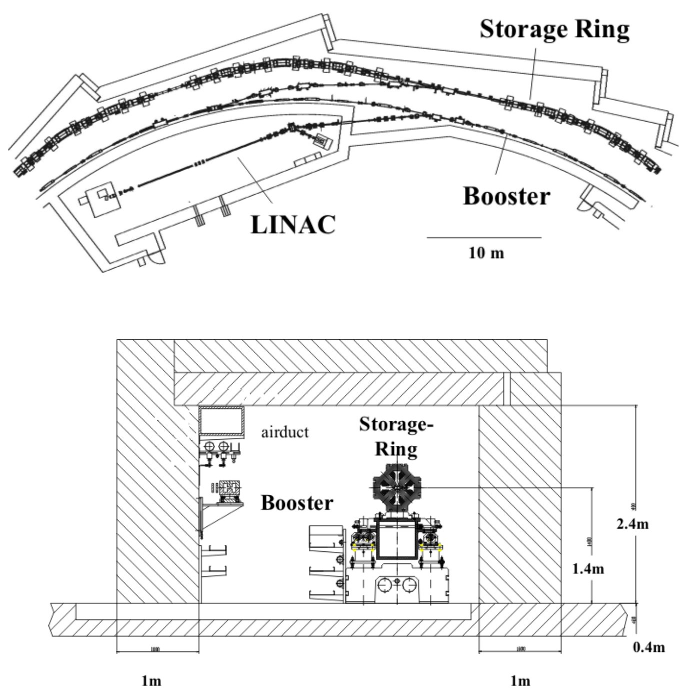

Fig. 1. Facility layout and section through the booster and storage ring tunnel

The SLS/PSI building has the shape of a doughnut with an outer diameter of 138 m, an inner diameter of 32 m and a height of 14 m. The building is divided in five different zones labeled in Fig. 2.

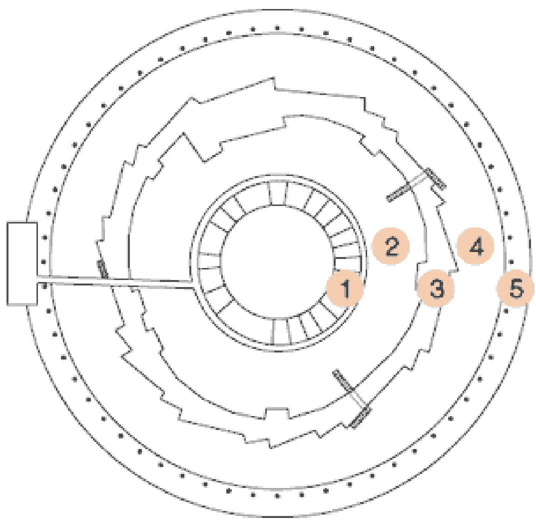

Fig. 2. Ground plan of SLS/PSI building;
1: office building, 2: technical gallery, 3: tunnel housing the storage ring, booster and linear accelerator, 4: beamline area 5: outer ring.

An auxiliary building houses the bulky equipment of the technical infrastructure, like pumps and storage tanks for the cooling system and the primary distribution of the electrical power. Of interest for this paper is the behavior of the test platform and the vibrations on the test platform during operation.

Synchrotron ALBA in Barcelona, Spain

ALBA, the first Synchrotron Light Facility in Spain, is in construction phase for the time being. It will be a complex of buildings with roughly 13,500 m^2 for housing the accelerator, the experimental hall, the infrastructure, scientific and technical personnel and the administration.

The ALBA facility consists of the following three building modules:

- Main Building. This building houses the accelerators, power and control units.
- Technical Buildings. They house the heavy support infrastructure, i.e. the cooling plant and the electrical sub-plant, the service workshops for water, electricity and gas.
- Administration area. It comprises the offices for the administration and for in-house personnel, the entrance with the reception area, as well as library, educational exhibits room, conference room and cafeteria.

A situation of the Main Building as well as a section is shown in Fig. 3, together with the relevant dimensions. The outer and inner diameters of the main building are 126 m and 49 m respectively.

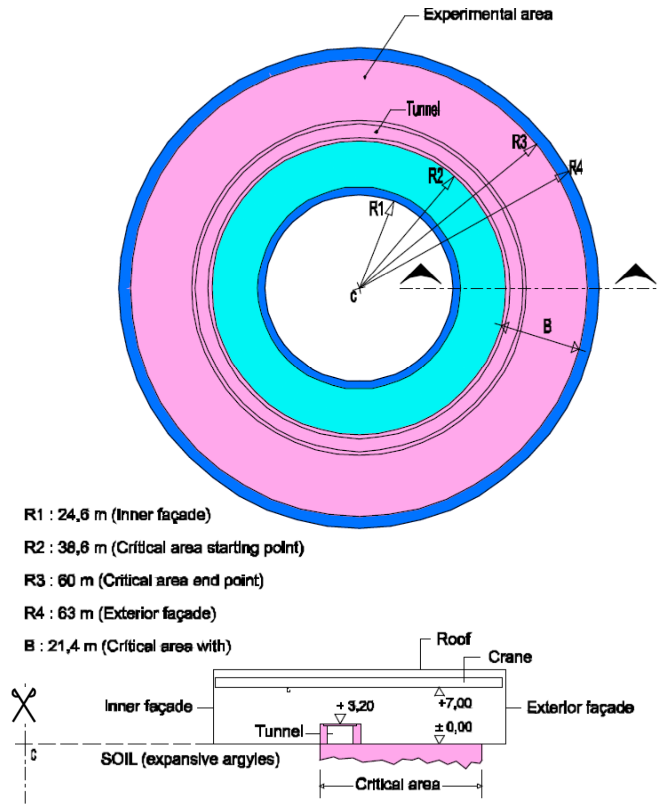

Fig. 3. Ground plan and section of main building at ALBA

Starting at the centre, the areas are divided into an interior court yard, an inner passageway, the service area, the experimental area and an outer passageway.

SUBSOIL CONDITIONS AND VIBRATION SOURCES IN THE VICINITY

SLS/PSI site

Subsoil conditions. The subsoil conditions at the SLS/PSI site are very favorable. The whole building is "floating" on a 12 m thick layer of densely packed terrace gravel (sandy gravel matrix with sand and silt lenses) formed during the last glacial period, lying upon the bedrock. The water table is very low and can be considered as constant over the course of a year. This subsoil (with the exception of the topmost meters) can be considered as a homogeneous material.

Vibration sources. The SLS/PSI facility lies in a rural area without disturbing vibration sources in the neighborhood, except installations in other PSI facilities nearby.

ALBA site

Subsoil conditions. The layering of the subsoil at ALBA site, Barcelona, is very inhomogeneous. The subsoil can be considered more as a "lens-type" structure than as homogenous layers. In addition, there is an erratic fluctuating ground water table.

The main material types are sandstones and marls. The subsoil formations consist partly of swelling materials. The results of extensometer measurements showed irregular patterns of swelling and shrinking periods. Remarkably, even at depths of about 40 to 60 m below surface, deformations up to about 1 mm have been measured. At a depth of about 10 m below surface, shrinking of up to 6 mm and swelling of 7 mm in irregular patterns have been measured in the region of the future test area.

To evaluate the ground movements caused by potential changes of the hydrogeological conditions at the site, several in-situ field tests (pressuremeter tests, SPT etc.) and laboratory tests (direct shear, unconfined and triaxial compression tests, consolidation and swelling characteristics) have been performed. Especially relevant in this case are the monitoring devices installed in the boreholes, consisting of sliding micrometers, extensometers, inclinometers and piezometers.

The subsoil materials are classified mostly as CL. The general mineralogy shows mean values of over 50% of clays, 20% quartz, 20% calcite, 10% feldspar. Of the clay fraction, illites make around 40% (up to 100% at depths around 40-50 m), smectites 40%, clorites and caolinites 20%.

Vibration sources. In the neighborhood of the ALBA synchrotron, a tile factory with significant appurtenant truck traffic is located. Additionally, at the lower end of the property is one of the main roads to Barcelona.

Measuring the natural vibration level at the beginning of the design phase was mandatory. One has to be aware of the fact that particularly in the long period range an excessive natural vibration level could lead to a situation where the stringent requirements cannot be fulfilled. For the measurements in the low frequency range special equipment and experience was needed.

SOLUTIONS FOR TEST AREA FOUNDATIONS

General considerations

Settlements. While the absolute settlements are of no particular importance for operation, major differential settlements would lead to additional periodical adjustments. Differential settlements depend on the homogeneity of the subsoil and (in case of non-homogeneous conditions) on the plate thickness.

Vibrations. Two cases have to be distinguished for the consideration of vibration issues of the test plate: vibration sources located directly on the test plate, and vibration sources located outside the test plate.

In the case of vibration sources located outside the test plate, the best solution to minimize vibrations on the plate would be to isolate the plate against the subsoil by means of springs, or by creating a major impedance step between different soil layers.

In contrast, to limit the vibration amplitudes caused by equipments located directly on the test plate, an isolation of the plate would not be beneficial. In the very low acceptable deformation level in the present cases, there is nearly no material damping in the test plate. Therefore, all activities on the test area produce nearly undamped vibrations. A plate direct founded on the subsoil would be the best solution, since this would lead to a so-called "geometrical damping" or "system damping", where energy is dissipated into the underground half space.

The major challenge is to find an appropriate solution for these two conflicting issues.

Solution for the foundation of the test plate at the SLS/PSI site

As discussed above, the highest system damping is achieved by connecting the test plate firmly with the subsoil. This maximizes the system damping for vertical and horizontal vibrations near 100% of the critical damping, which leads to nearly no resonance overshooting. In the case of SLS/PSI, this solution can be considered in the first place as the best solution.

The most favorable subsoil conditions allowed, after a parametric study of the potential thickness of sand and silt lenses, for a very slender slab foundation construction (of only 40 cm thickness), compared to the dimensions of the facility.

Solution for the foundation of the test plate at the ALBA site

Considerations on a spring foundation. A classical solution to meet unfavorable conditions such as those encountered at ALBA site would be the foundation of a stiff plate on elastic supports (steel springs, synthetics) to better distribute the inhomogeneities of swelling and shrinking. Unfortunately, due to the extreme criteria, this solution to minimize differential deformations on the test plate has a tremendous unfavorable influence on the behavior of the test plate in respect to vibrations, as previously discussed. Moreover, maintenance and regular inspections in case of spring elements are mandatory, and the construction costs are significantly higher than for a stiff test plate directly founded on the subsoil.

Rating: The solution with a spring foundation is not taken into consideration, on one hand due to the difficulty to meet the vibration requirements, on the other hand due to the high construction and maintenance costs.

Considerations on a pile foundation of the test plate. To compensate the differential deformations at the surface, a pile foundation is a potential solution to solve the swelling and shrinking problem. A disadvantage of this solution, which cannot be well controlled, is that changes in the general pattern of the water table can occur by constructing the piles, able to producing higher swelling and shrinking deformations. To compensate for this risk, the foundation of the piles would have to be sufficiently deep.

Two solution types could assist in solving the swelling and shrinking problem:

- Pile foundations with large piles up to a depth where swelling and shrinking deformations are minimal. As shown in the discussion of the geotechnical conditions of ALBA site, the piles would have to go up to a depth of about 40 to 60 m.
- A large number of micropiles under the test area, which would lead to a certain homogeneity of the subsoil conditions by distributing swelling and shrinking effects. Trough skin friction of the piles, shrinking and swelling would be distributed in the subsoil body within the piles. A typical construction would be micropiles with a diameter of about 50mm, a length of 40m, a distance to each other of 2m, with a surrounding body of mortar injections.

The second solution with micropiles is more promising, since it leads to a homogeneous distribution of swelling and shrinking effects under the test area. At the same time, the contact of the test area with the subsoil is kept, such that the system damping is located on a high level.

Rating: This solution would correspond to conventional building practice, no maintenance would be needed, and the required lifetime is guaranteed. However, very high construction costs for the micropiles would have to be taken into account.

Selected solution. Taking the several considerations into account, a stiff area foundation directly founded on the subsoil was selected as the most promising solution at the ALBA site. The advantages of the selected solution are that it is a simple and economic construction, where no further maintenance is needed.

Parametric studies considering the shrinking and swelling characteristics of the subsoil led to an experimental plate with a thickness of 1.80 m. Figure 4 shows the results of a calculation based on this plate, where on the right side a swelling deformation of about 8mm is assumed. The resulting equidistance lines showed that the requirement of a differential deformation of maximum 0.25mm per 10m (which is dependent on the curvature of the plate) can be met.

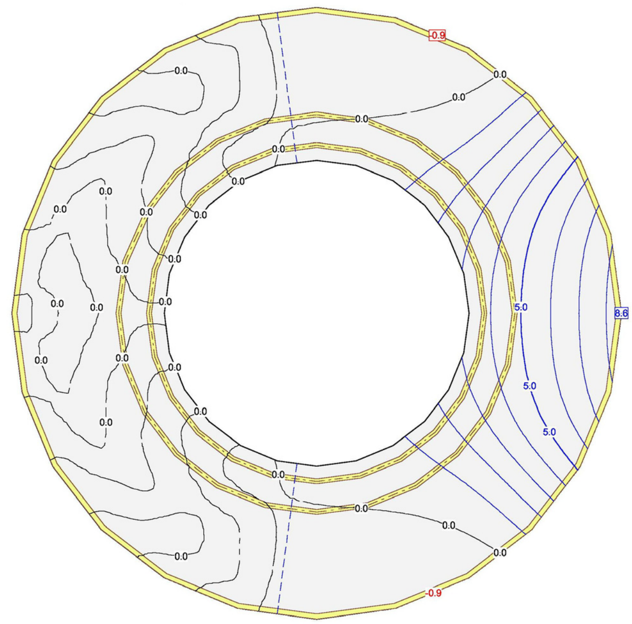

Fig. 4. Example of deformation pattern of a stiff plate directly founded on the soil

Due to the interface (impedance drop) between the subsoil and the stiff plate, only a part of the external vibrations would be transmitted to the plate. From this point of view, a large number of impedance drops would be ideal to minimize the effects from external vibrations. An additional measure taken at ALBA site is therefore the placement of a gravel layer underneath the concrete plate and can be regarded as a trade-off between two extremes: On one hand, the external vibrations can be further reduced to some extent due to the additional impedance drop, on the other hand the system damping of the plate is not significantly reduced (due to the low value of the impedance drop), particularly if it is taken into account that the system damping still remains over 100% due to the dimension of the plate. This solution is a way to optimize the reduction of vibrations coming from outside of the test plate and the vibrations produced directly on the test plate. Numerical simulations of the vibrations produced by sources located outside the test plate show promising results.

One of the main drawbacks of a plate directly founded on the subsoil is that there is no effective second line of defense in case of not fulfillment of the requirements. A possibility is the construction of trenches to hinder the vibration transmission. , depending on the subsoil conditions and the frequency band, But even with favorable conditions, a maximum reduction of 60% of the maximum value is possible.

The concept of the foundation of the test area directly on the subsoil has been successfully implemented at the SLS/PSI site. This concept is therefore being transferred to the ALBA synchrotron facility, which is in construction at the time being.

ADDITIONAL MEASURES TO REDUCE VIBRATIONS

Vibration sources outside the synchrotron facility

The vibration level reduction for external sources strongly depends on the frequency content of the vibrations and the stiffness properties of the subsoil and the test plate.

Vibrations originating from nearby roads strongly depend on the smoothness of the street surface. Passenger cars do not produce high vibration levels, whereas heavy trucks moving on a road with plenty of chuckholes produce significant vibrations. Regular maintenance of the road is therefore very important.

Vibrations produced from nearby factories or other vibration sources in adjacent properties could in principle be reduced by trenches. Unfortunately, in a geological situation as encountered on the ALBA site, trenches are not fully effective, due to refraction and reflection effects at the different layers. The needed depth of the trenches depends on the frequency of the vibrations and the length of the Rayleigh waves. Broad-band frequency vibrations are therefore difficult to reduce. The location of potential trenches would have to be carefully investigated because in certain areas the trenches lead to an enhanced vibration level compared to the situation without trenches (due to reflection effects). For these reasons, trenches have not been taken into consideration in the presented projects.

Based on experience, it can be said that the vibration reduction on the transition between the subsoil and the stiff plate is very high in the high frequency range (20 Hz and higher), considerably decreasing for the low frequency range, until only a small to negligible reduction at around 1 Hz is achieved. No reasonable countermeasures are possible to reduce the vibration level at very low frequencies.

Vibration sources outside the test ring, but inside the synchrotron facility

The following concepts for technical equipment located outside of the test area have been successfully implemented at the SLS/PSI site and are also transferred to the ALBA site:

- The final location of equipments producing strong vibrations or low frequency vibrations is selected in order not to further enhance the vibration level due to their location in the appurtenant building (ground floor, first floor etc.).
- The monoblocks (for air conditioning) are isolated with a system of steel springs. The air supply conduit is disconnected by an elastic sleeve from the monoblock, to avoid vibration transmission. The heat exchanger is connected with two compensators in horizontal and vertical directions to isolate vibrations.
- Other technical equipment producing vibrations are located as far as reasonable from the test area and are individually isolated on concrete blocks with synthetics against vibrations. A potential problem could arise if the most suitable isolation frequencies for pumps approximately coincide with the eigenfrequency of the soil deposit. This issue is carefully taken into account.
- All pipe connections between vibration source and test area are disconnected by compensators in vertical and horizontal direction. The selected compensators have a high flexibility and softness.

It is important to note that the isolation frequency has to be carefully chosen. On one hand, the lower the frequency of the damping system is, the more high-range frequencies are reduced. But only a low energy reduction takes place, due to the generally low damping characteristics of isolating systems.

Furthermore, to avoid resonant coupling, it is important to make sure that the eigenfrequency of the isolation system does not coincide with the eigenfrequencies of the underground, the test area or the structural eigenfrequency of technical equipment.

Vibration sources on the test area

The general measures for equipment located directly on the test area correspond to the above discussed measures. The number of equipment on the test area should of course be minimized. The reduction of the vibration level for sources on the test plate is accomplished by isolating the single equipments against the test plate. As previously discussed, the finally selected direct foundation of the test plate on the subsoil allows for a high energy radiation leading to a high system damping.

Potential vibration transmitted by the roof

The roof foundation is not connected to any part of the test area. Changing weather conditions, like wind and temperature, do thus hardly affect the tunnel and the beam lines.

The depth of the roof foundation is lower than the corresponding depth of the foundation of the test plate area. This enables to minimize the transfer of vibration from the roof to the test area.

CONCEPTS FOR THE CONSTRUCTION OF THE TEST AREA SLAB

SLS/PSI site

In the case of SLS/PSI synchrotron, a concrete test plate of 40 cm thickness suffices to meet the requirements in respect to deformations and vibrations. This slender construction is possible because of the excellent subsoil conditions.

Nevertheless, the excavation works had to be carefully performed in order not to disturb the natural dense packing of the subsoil materials. Normal excavation works were performed up to a depth of 50 cm above the foundation level. The remaining excavation was done by excavators with toothless buckets (overhead, to minimize the disturbance of the foundation layer). Only the upper 3 to 4 meters disturbed layers were excavated.

Locally encountered silt and sand lenses were removed and replaced by lean concrete in few cases, if their dimensions exceeded a certain limit determined by parameter studies conducted to minimize the differential displacements.

ALBA site

In contrast, at the ALBA site a concrete test plate with a thickness of about 1.80m over a gravel layer meets the defined requirements. Such a stiff construction is needed to meet the requirements on differential displacements, taking into consideration the potential swelling and shrinking characteristics of the soil.

Some concepts in the construction of the test area slab at the ALBA site are presented below.

Excavation Phase. The main goal in the excavation phase is to minimize the alteration of the hydraulic conditions of the underground. The potential deformations of the subsoil materials due to constructive interventions are therefore reduced to a minimum by the proposed procedure.

The concept for the preservation of the hydraulic conditions includes the following phases:

- Surface water originating from the hill side of the area is drained by means of a concrete culvert in order to preventing it to reach the excavation grounds.
- Excavation and slope stabilization at the hill side of the synchrotron.
- First excavation up to appurtenant structure foundation level and covering of the excavation area by means of lean concrete (5 to 10 cm) to prevent pluvial water intrusion into the subsoil. This should mainly prevent to alter the hydraulic conditions of the material lenses with potential subsoil deformation.
- If needed, replacement of unsuitable subsoil material.
- Installation of a leveling measurement system in the test area to monitory the surface movement. During the whole construction phase, performing of leveling measurements to check the surface movements. A certain lift can occur due to the unloading of the soil.
- During the successive excavation for the test area foundation, including the foundation for the roof, rain water intrusion is prevented (by means of 5 to 10 cm lean concrete).
- The test area foundation consists of 1 m well compacted sandy gravel, covered by 5 to 10 cm lean concrete. The work for the treatment of the area foundation (with lean concrete and gravel), is carried out under dry conditions.

During construction, all rainwater is collected and drained beyond the construction site. A permanent drainage system around the facility area is established at the foundation level. A separate system is likewise constructed for the test area alone.

Slab Construction. Concreting a 1.80 m thick concrete plate produces a high temperature within the slab due to the hydration between cement and the water during the first hours of hardening. This effect could cause substantial cracks in the new concrete slab. To reduce this risk, the whole slab is divided into several single elements. The construction joints between the single segments are vertical with reinforcement going through and the concrete surface roughened after pouring. The single elements are poured within one day, using pumping concrete. The sequence of pouring the single segments is shown in Fig. 10.

DISCUSSION AND CONCLUSIONS

The considered facilities as well as the soil conditions at the sites were briefly discussed. General design criteria to meet the deformation and vibration requirements were then given.

It was shown that meeting the vibration criteria is more difficult than the deformation criteria. Furthermore, if the criteria for deformation of the plate are not fully fulfilled, there still exists the possibility of adjusting the equipment, if only within a limited range. This is of course not desirable, but would not definitely hinder the operation of the synchrotron, whereas not meeting the vibration criteria would lead to a significant quality reduction in the operation of the synchrotron. Therefore, the vibration criteria are more or less "go / no go" criteria.

It has also to be mentioned that the measuring of the natural vibration level at the site at the beginning of the design phase is mandatory and crucial. A high vibration level, particularly in the very low frequency range, could jeopardize the operation.

During construction, in any case, precautions must be taken to avoid moisture changes in the subsoil.

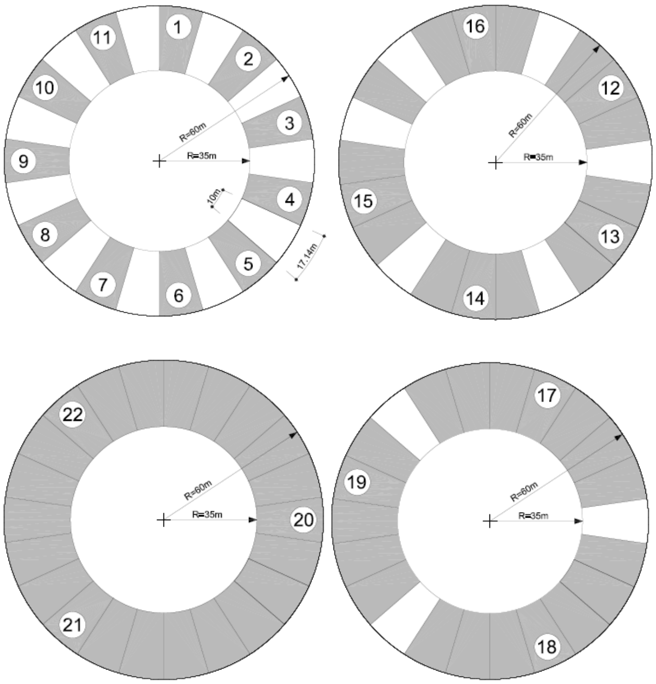

Fig. 10: Sequence of pouring the single elements of the test area slab

AKNOWLEDGEMENTS

PSI/SLS Site

Paul Scherrer Institut, Villigen PSI, Switzerland.

ALBA Site

CELLS Consorcio para la Construcción, Equipamiento y Explotación del Laboratorio de Luz Sincrotrón (Consortium for the Exploitation of the Synchrotron Light Laboratory); co-financed by the Spanish government and the Catalan government.

Master Ingenieria Arquitectura, Barcelona, Spain. http://www.masteringenieria.com

REFERENCES

SLS/PSI Homepage http://sls.web.psi.ch/ (2002)

ALBA Homepage http://www.cells.es/ (2005)