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Construction and Seismic Analysis of Swissmill Tower in Zurich, Switzerland

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ABSTRACT

Silos belong to the most important and strategic buildings for any country. In this regard, their operation without any interruption is vital. Moreover, it is necessary to take into account their remaining lifetime and required capacity for future needs. From this aspect, the capacity of the existing silo 57 of Swissmill in Zurich is increased by erecting the new Swissmill tower. This tower is the heaviest and second tallest building in Zurich. Moreover, it is the highest grain silo all over the world. Major challenges of this project were the construction around and above an existing silo being always in operation, the limited construction site, the interaction of old and new structure and the location at the river bank. Due to the importance of the building and its potential danger to environment in failure cases of the load-bearing structure, earthquake analysis was carried out using a 3D finite element model, which includes the entire structure and the soil under the silo. Current article is about construction and seismic analysis of the new Swissmill tower in Zurich, Switzerland. The paper is divided into a construction and an analysis part. In the construction part general overviews of project organization and execution stages are discussed. In the analysis part, the 3D-models of the silo, subsoil including the piles used for the earthquake calculations are described.

KEYWORDS: *Silo, Construction management, Earthquake analysis, High-rise building, Soil-structure interaction*

1. INTRODUCTION

Silos belong to the strategic buildings in any country due to their supplying tasks. In this regard, their sustainability is essential to provide needs of society continuously. Hence, it was necessary for Swissmill to increase the silo capacity in Zürich. The older still existing silo of Swissmill is named silo 24 and was constructed in 1924. Later, silo 57 was erected in 1957. The evaluation of projects for future capacity requirements results in increasing the capacity of the existing silo 57 by erecting the so-called Swissmill tower or Kornhaus, located in the Limmat Valley in Zurich, Switzerland (Grob 2016).

Satellite view of the construction site is shown in Fig.1. As it is evident, the silo is located at the river bank. Therefore, poor soil condition would be highly expected. On the other hand,available space in order to be used as construction site was significantly limited. The other important factor, which should be noticed, is the extremely important railway bridge passing over Limmat River nearby the construction site. Any interruption or failures in silo may have catastrophic economical losses not only due to its inherent importance but also due to train transportation disturbance. All these conditions, made project design, management and execution such difficult and require precise tasks.

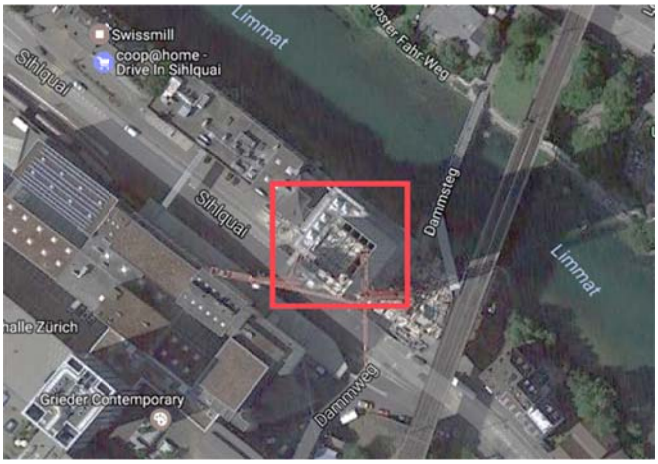


Fig. 1 Satellite view of silo's location

Finally, capacity-increasing aim is achieved by adding a new silo above the existing one. The height of building is increased from 42 m to 118 m. The building's status before and after construction is shown in Fig.2. The new parts are constructed by slip forming method in five working shifts. Moreover, the width of the silo is broadened on the roadside and a row of cells on the riverside is replaced by a stronger new one. At the end, the total weight became approximately equal to 80,000 tons (Mohasseb 2015). Considering all, the new silo is the heaviest and second tallest building in Zurich. The total sum of planning and construction costs amounts 35 Million CHF, of which 25 million CHF are for the structure (Grob 2016).
The Swissmill tower belongs to Swissmill, a firm of Coop production. Swissmill is the largest flour production plant in Switzerland and provides approximately 30% of the whole country's requirements by operating 800 tons of grains each day. In the current article, for the Swissmill tower the structural concept, construction and planning duties and seismic analysis efforts are briefly discussed.

(a) Existing silo (b) after construction the new silo

Fig. 2 View of the existing and new silo

2. STRUCTRUAL CONCEPT

The load-bearing structure structure of Swissmill tower consists of two parts, the structure of the existing silo 57 and the added new structure to build up the Swissmill tower. The load-bearing structure of Swissmill tower behaves as a monolith composed by the structure of the existing silo 57 and the added new one.

Generally, the gray parts in the following figures show the existing old structure while the green parts show the added new one.

Two new silo cell rows and two new transverse walls were constructed around the existing silo 57 up to a level of 42m above terrain, as it is shown in Fig.3. Obviously, the big weight of the upper part is transferred to bedrock by the lower new silo cell rows and the transverse walls, by the pile caps and the piles. 49 piles were constructed for such aims. The diameter of piles is 1.50 m and their approximate length varies from 40 m to 50 m (Grob 2016).

Detailed investigations of the structure of the older silo 24 have shown that it could be severely damaged or destroyed due to movements of the new Swissmill tower, in case of missing joint above the terrain. The new intermediate structure (small green part on left side in section LS) is monolithically connected to the silo 57, while it is separated from silo 24 above terrain. Thus, the old silo 24 is no longer endangered by dynamic vibrations of the new Swissmill tower. Likewise, the connection between the new intermediate structure and the old silo 24 had to be detailed in a way that no great forces are transferred to the old silo 24. In addition, the joint between silo 24 and the new intermediate structure was covered by a surrounding metal sheet in order to prevent weathering (Grob 2016).

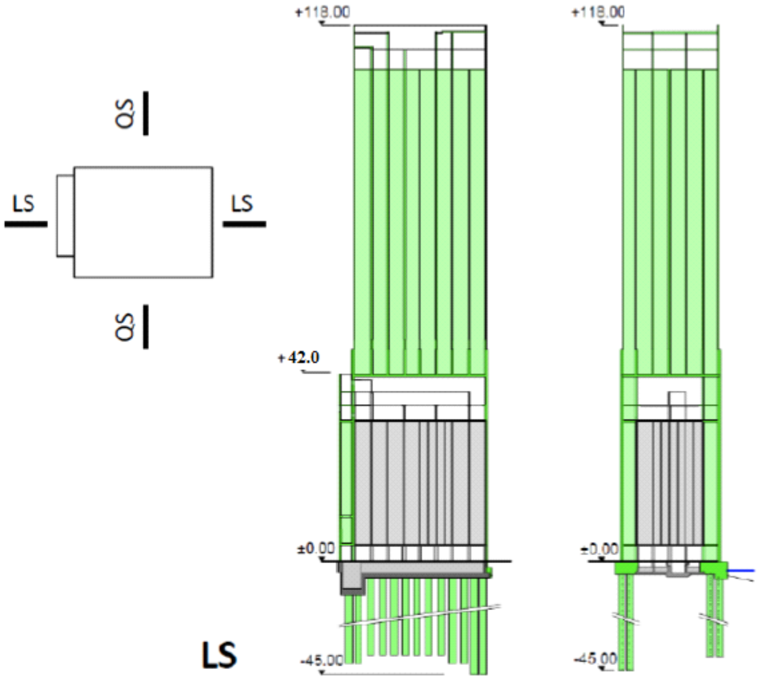


Fig. 3 Cross section (elevation view) of existing and new silo (Grob 2016)

Because of the already mentioned poor structural condition of silo 24, it was reinforced locally by steel supports. During construction, it was found that a part of the outer wall of silo 24 is not a concrete wall as previously assumed, but a masonry wall. In order to reduce risk of collapse, the masonry wall is immediately secured in the critical area by fastening of steel girders.

First, the 49 piles and the two pile caps were constructed in construction stages 1 and 2 (red numbers 1,2 in Fig.4). In these two construction stages, the two new lower cell rows and the eastern sidewall (transverse wall) were constructed up to a level of 42m above terrain. Then, in construction stage 3 (red number 3 in Fig.4) the old small intermediate part between silo 24 and silo 57 was replaced by a new intermediate part, and the new western transverse wall was constructed up to a level of 42m above terrain. Later, the upper silo was erected in two construction phases (red numbers 4,5 in Fig.4) due to logistical considerations. At the end, in the construction stage 6 the upper silo was completed with the ceiling part.

One of the important challenges in design of the project is considering interaction between soil, flat foundation of existing silo 57 and new structure including piles. 3D finite element models are constructed to conduct dynamic analysis, of which the results will be illustrated in section 4 of this paper. Foundation section and position of piles are depicted in Fig.5.

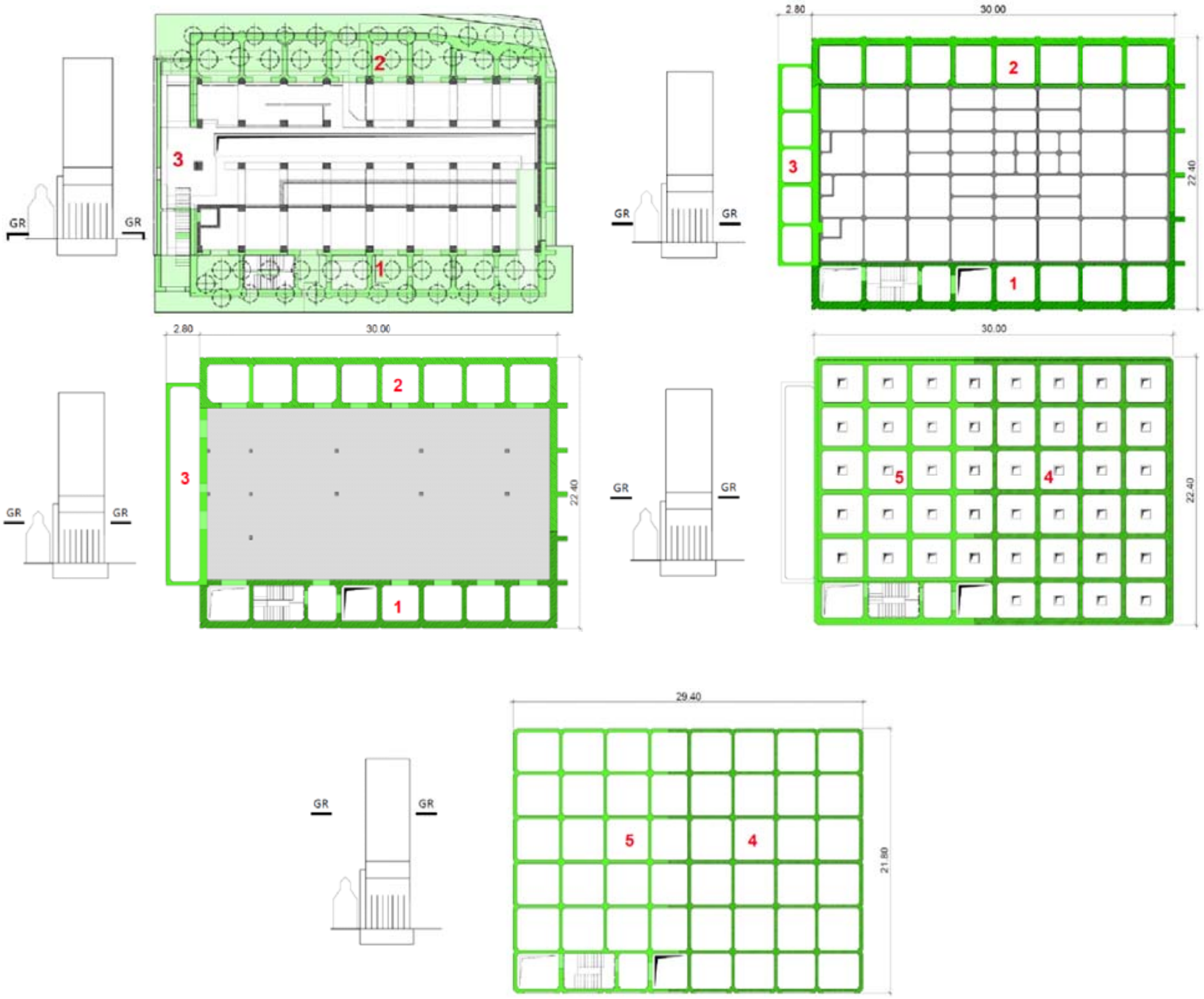


Fig. 4 Plan view on different height levels (Grob 2016)

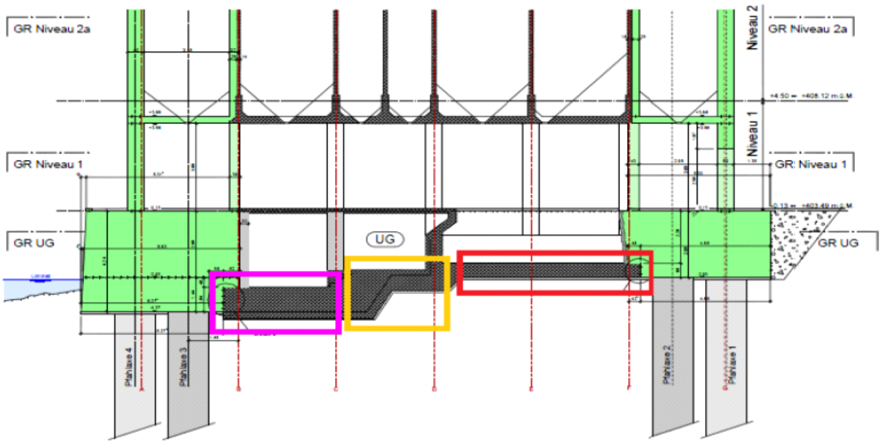
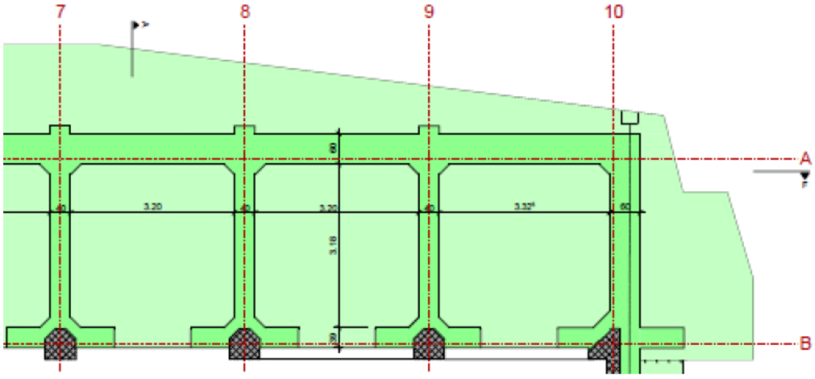
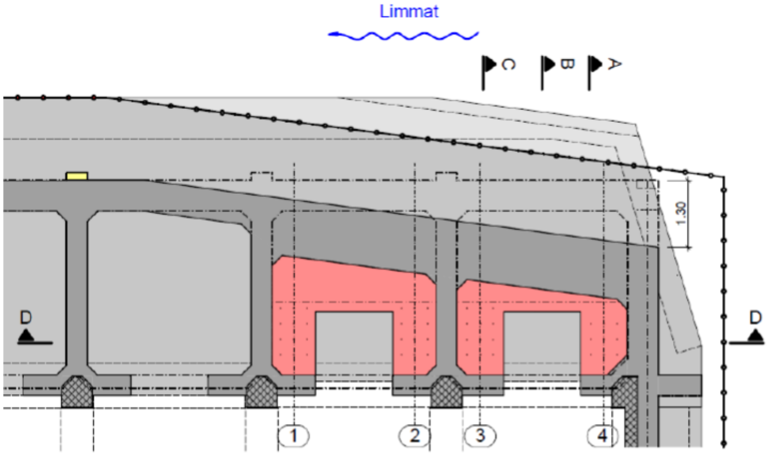


Fig. 5 Foundation section (Grob 2016)

The authorities of Zürich demanded space for a future public footpath along the river. Thus a cantilever situation, see Fig.6, had to be made in a silo corner on the riverside. This part is highly stressed due to stress concentration from above parts. It is strengthened by thickening the outer wall and installation of complex steel reinforcement. Later and during the second phase of the construction, demanding and uniquely distinctive investigations were made regarding to stresses under heavy loads and possible dynamic effects. These studies have shown that the load-bearing structure in this silo corner must additionally be reinforced by an internal concrete structure above the pile cap. This difficult reinforcement work was carried out under direct supervision of project engineer Dr. Josef Grob. It began in mid-September 2015 and was completed in a perfect quality at the end of January 2016. Plan view and inner reinforcement of this part are shown in Fig.6.



(a) Plan view of upper part (Grob 2016)



(b) Inner reinforcement

Fig. 6 Plan view of lower part with internal reinforcement (Grob 2016)

3. PROJECT PHASES AND CONSTRUCTION STAGES

From general aspect of view, the project could be divided into two major phases. From September 2012 until June 2014, the planning phase took place. Dr. J. Grob & Partner AG has done the Engineering project. In this phase, the architects Harder Haas Partner AG were responsible for the architecture and for the general planning in cooperation with ENSECO Ltd.

The Swissmill Tower is a typical engineering structure. Thus the project organization has been changed for the second major phase in which the execution of the Swissmill tower took place. the contractor ARGE Kornhaus (Implenia Schweiz AG / KIBAG Baudienstleistungen AG) has taken the responsibility of a general contractor In this phase Dr. J. Grob & Partner AG worked as subcontractor of ARGE Kornhaus and performed the civil engineering works as well as the coordination with the architects and the Bühler Group (silo installation), see Fig.7.

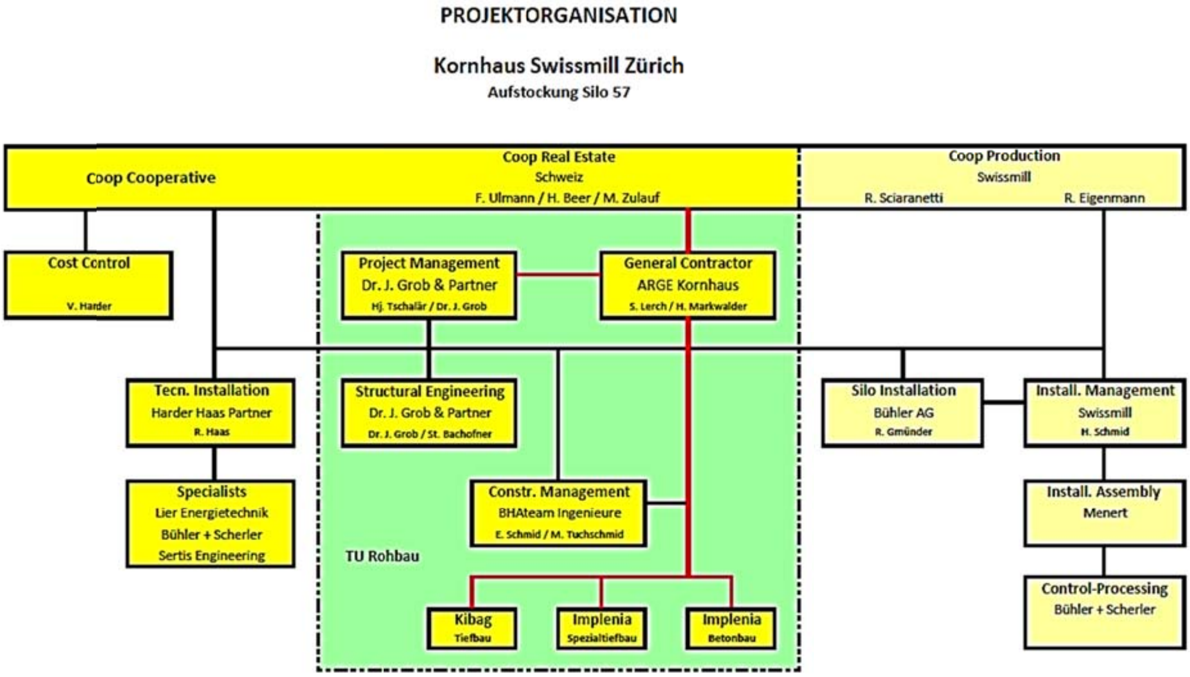


Fig. 7 Project organization of second phase (Grob 2016)

Fig. 8 Completed construction stage 1

Fig. 9 Completed construction stage 4 execution

Fig. 10 Construction stage 5 in

Considering all, the execution phase lasted from spring 2013 till the end of 2015. The Swissmill tower is completed in six different stages. They could be summarized as follows (Grob 2016):

- **Stage 1**: Demolition of existing workshop, foundation, new cell row on Sihlquai side (roadside) and first part of the new eastern sidewall up to 42m height [Fig.8]
- **Stage 2**: Demolition of existing cell row, foundation, new cell row on Limmat side (riverside) and second part of the new eastern sidewall up to 42m height

This stage includes construction works in the river Limmat.

- **Stage 3**: Replacement of the intermediate part with new western transverse wall
- **Stage 4**: Mounting construction of eastern part of new upper silo [Fig.9]
- **Stage 5**: Mounting construction of western part of new upper silo [Fig.10]
- **Stage 6**: Construction of ceiling part of new upper silo

4. SEISMIC ANALYSIS

Instrumentally recorded ground motions in Switzerland between 1975 and 2014 are shown in Fig.11. As it is evident, Zurich is located in a median seismic region.

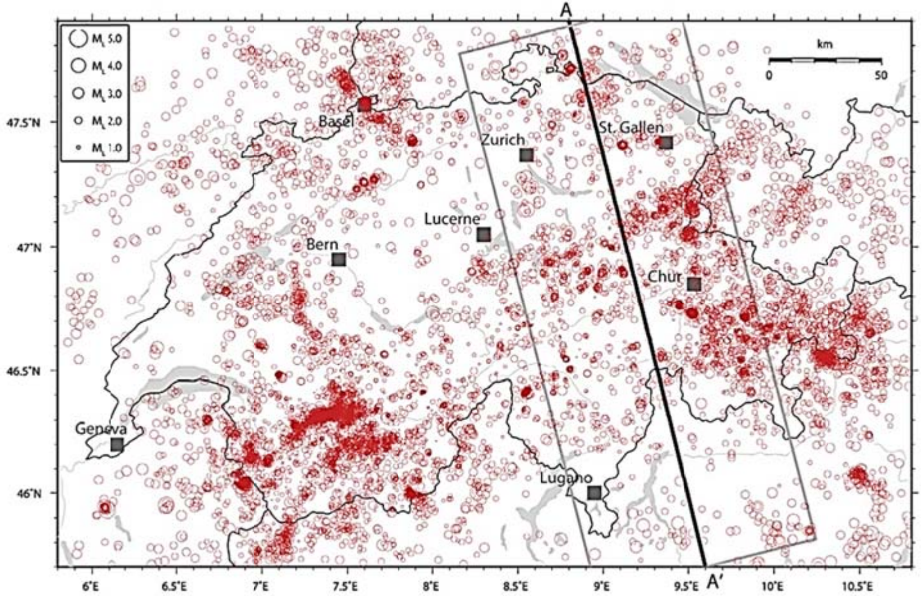


Fig. 11 Instrumentally recorded earthquakes in Switzerland between Jan 1975 and Jan 2014 (Mohasseb 2016)

Moreover, Swiss probabilistic peak ground acceleration hazard map is shown in Fig.12. As it is evident, Zurich is between 60 and 70 cm/s^2 (0.06-0.07g). Therefore, possibility of major earthquake occurrence at studying site would not be significant. In spite of that, it should be noticed that weak site soil condition can amplify earthquakes.

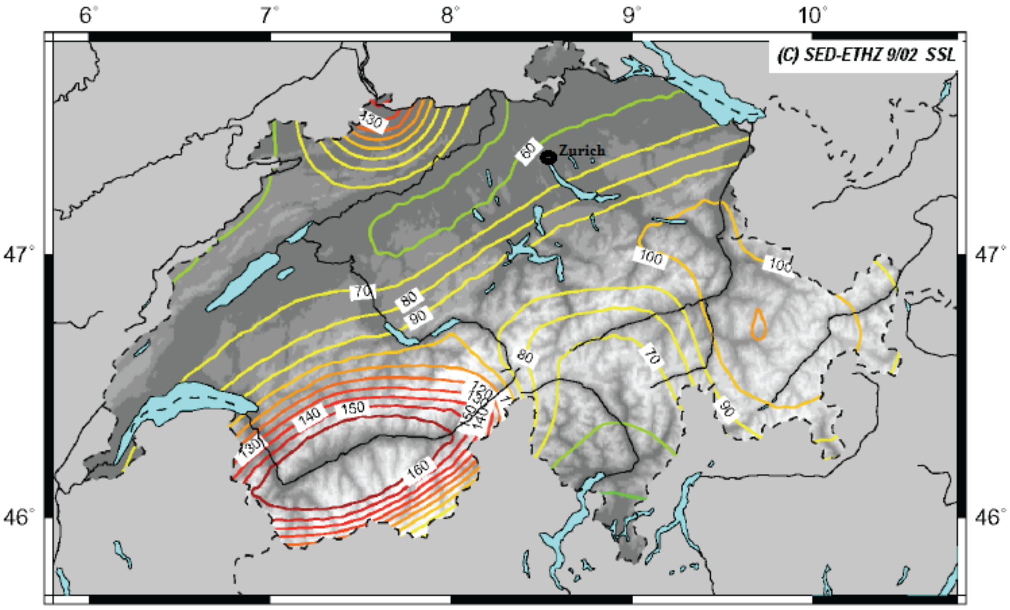


Fig. 12 Probabilistic hazard map of Switzerland showing the peak horizontal ground acceleration (a_{gd}) in cm/s^2 (Wenk 2014)

Such amplifications are reported in past earthquakes. For instance, Michoacan earthquake (Mexico) at 1985 with magnitude of 8.1 had an epicenter 350 km away from Mexico City. This earthquake produced accelerations equal to 0.04g at rock sites, while recorded accelerations at soft soil sites were up to 5 times greater than those at rock sites. Therefore, soil-structure interaction should be considered. Soil condition includes different layers of the site.

In order to extract demands on the building, 3D finite element model using ADINA software is constructed and linear analysis are conducted. The model has more than 3,000,000 elements. The structure is modeled using shell and solid elements (Mohasseb 2015, Bathe 2006). Soil-structure interaction is considered by assigning equivalent springs and dashpots located under foundation. General concept is shown in Fig.13. In cases which fundamental frequency of the building is less than frequency of site, no radiation damping is expected (NIST 2012). This phenomenon is due to existence of the cutoff frequency. First frequency of site soil is 0.9 Hz, which is greater than 0.3 Hz of the structure. Therefore, no radiation damping is considered (Mohasseb 2015).

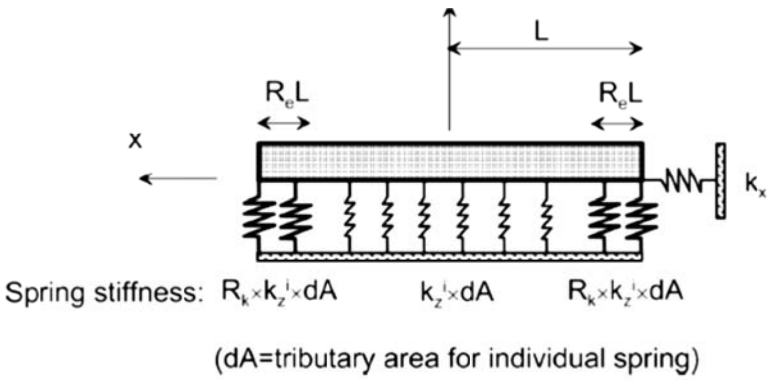


Fig. 13 Spring and dashpot to model substructure (NIST 2012)

Soil stiffness is calculated by means of cone method. Cone method or strength of material method is based on the fact that vibrating waves at the interface of two layers will reflect and refract. Finally, it would be like a bar with changing cross section and without mass. Fig.14 summarizes the concept of method (Wolf 2004). The spring constant for individual pile in foundation system is calculated as 890,000 kN/m, while considering group effect causes total horizontal stiffness to be 1,800,000 kN/m (Mohasseb 2015, Kaynia 1982). It is valuable to mention that interaction between old and new silo is taken into account by reducing stiffness of these springs by factor 1.5. Besides the stiffness, foundation input motions could be calculated by this approach. Frequency modification is applied to modify ground motion on bed rock level to ground motion under foundation. Then, inverse frequency transformation is conducted to obtain ground motion record in time domain. Executable program named as "CONAN" is developed for aforementioned method. The earthquake accelerations on the site are amplified by a factor of 2 compared to bedrock accelerations. Obtained wave propagation from cone method is depicted in Fig.15.

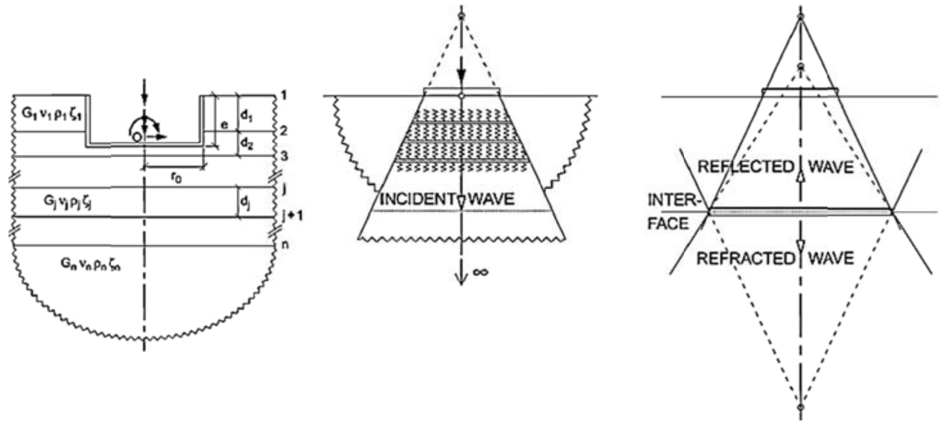


Fig. 14 Cone method's concept (Wolf 2004)

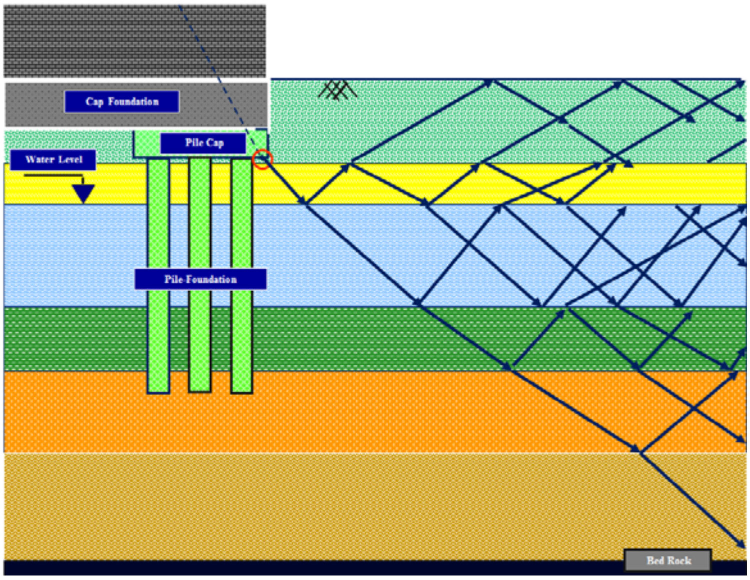


Fig. 15 Wave propagation from cone method

Finally, first Eigenperiod is obtained as 3.1 Sec (Fig.16). In order to control roof displacement under possible ground motion, Duzce record is applied to the model. The maximum roof displacement approximately equals to 21 cm.

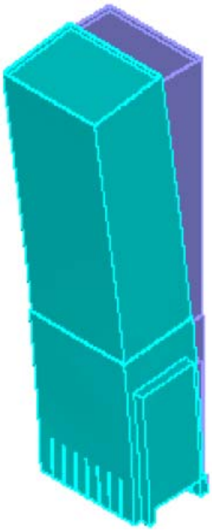
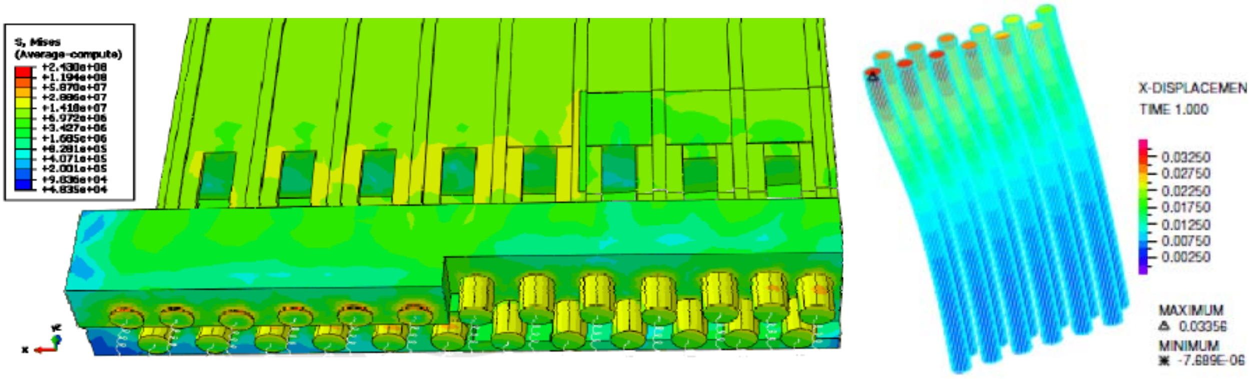


Fig. 16 First mode of vibration

At the end, von Mises stresses and lateral displacement of piles using load combination of dead loads and earthquake are calculated. Horizontal displacement of foundation under earthquake excitation equals as 3.1 cm. In addition, axial force and bending moment of piles equal to 19,000 kN and 3,430 kN m, respectively Fig.17.



(a) von Mises stresses at piles and cap foundation (b) pile displacements

Fig. 17 Stress and displacement at foundation level (Mohasseb 2015)

5. CONCLUSIONS

The article is about the new Swissmill tower or Kornhaus in Zurich, which was erected by increasing the capacity of the existing silo 57. It is constructed around and above the old silo 57. The tower belongs to Swissmill, the largest flour production plant in Switzerland, which provides approximately 30% of the whole country's requirements of grain products. Major design and construction challenges were the construction around and above an existing silo being always in operation, the limited construction site, the soil-structure interaction, the interaction of old and new structure and the location at the river bank. The Swissmill tower is the second tallest and heaviest building in Zurich. Moreover, it is the highest grain silo all over the world. First, structural system is discussed; later construction phases and followed stages are described. At the end, seismic response of tower is investigated. In spite of being located in a region with intermediate seismicity; weak site soil condition could amplify earthquakes. Therefore, soil-structure interaction is taken into account. Substructure is modeled using springs and dashpots. Since, cutoff frequency phenomenon is detected, no radiation damping is expected. Finally, stresses, forces on foundation and roof displacement under earthquake excitation are calculated.

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