

INNOVATIVE DESIGN FOR RETAINING STRUCTURES USING COMBINED PRODUCTS

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Summary:

The execution of deep basement excavations under narrow conditions is one of the most challenging tasks in geotechnics. The vicinity of neighbouring buildings, roads, and underground structures such as sewers or power lines, quite often prohibits the application of standard solutions. In addition, legal considerations in the use of adjacent properties is becoming increasingly difficult. This paper presents some innovative approaches to overcome the above-mentioned challenges based on several case studies from central Europe. For every project the design approach as well as the techniques used for execution will be explained, detailing both the advantages and the limitations of the applications. One case study shows a deep basement excavation (approx. 17m) in the centre of Prague, Czech Republic. This project featured many challenging boundary conditions (narrow construction area, high ground water table, jet grouting column embedment into bedrock, constraints regarding use of ground anchors due to property rights, etc). The realisation of the complex design is described and illustrated in detail. Other case studies show the combined application of bored piles with jet grouting and also explain the design of vertical prestressed anchors for retaining walls.

Key words:

Innovative design, deep excavation, retaining structure, jet grouting

1. INTRODUCTION

The development of urban areas has always presented challenges, from access for equipment and materials to the rectification of existing foundations in unknown condition. Compounding these is the increasingly stringent requirements to retain, maintain and reduce impact on culturally and historically significant structures. As available space is becoming more limited, optimisation of real estate has resulted in buildings getting higher and their basements deeper below ground. Two or more basement levels are quite common, with typical excavation depths ranging from 5 to more than 10m. Additionally, we are faced with neighbouring buildings that are equally high, deep and massive. These buildings directly adjacent the retaining structure require underpinning to limit settlement, and in cases where they are within just a few meters, this building mass generates additional earth pressure for the retaining wall to support, resulting in complex loading cases.

This paper highlights several common challenges and explores the measures implemented to overcome them. The challenges and examples of either design based solutions or practical applications will focus on the following topics – the limitations of conventional geotechnical construction methods, overcoming challenging geology and the requirement for watertight basement constructions.

2. LIMITATIONS OF CONVENTIONAL METHODS

There is a wide range of techniques available that can solve some of the challenges outlined above. Each of them has its advantages but also limitations. The determination of the technique or combination thereof best suited to the application is often dependant on numerous parameters. Soil and ground water conditions and the dimension and arrangement of the basement excavation are key considerations. Of increasing importance is the legal considerations when wanting to utilise adjacent property subsoils for soil nails and or ground anchors required to complement a retaining system. A common solution is to install embedded walls in combination with one or more layers of ground anchors or internal struts. The walls are typically executed as secant pile walls or diaphragm-walls, the latter more suited to large projects offering sufficient space for the equipment required in construction of these elements. The application of soldier or contiguous pile walls is typically limited to excavations above the ground water table and jet grouting walls can be used under and in front of existing buildings. With sheet pile walls applicable for limited soil and depth conditions.

However, there are extensive reasons to consider alternative solutions. The vicinity of underground structures, power lines, sewers, etc. limit the application of ground anchors due to clearance or impact issues. Some European cities have prohibited the use of public ground during construction which also limits the use of ground anchors and nails as these are typically installed outside the building footprint into adjacent land. An additional consideration is the drilling procedure required to install anchors below the ground water table, it is technically very challenging and increases the risk profile of the project. Struts as substitutes for ground anchors heavily influence the construction sequence, and basement excavations with larger dimensions or non-rectangular/uniform layouts result in strutting systems being prohibitively difficult and expensive. To install stiff elements like piles, d-walls or sheet pile walls, large and heavy equipment is required to operate in limited or restricted space. Small and adaptive rigs are available to install jet grouting columns, but such retaining systems usually require additional layers of anchors or struts to compensate for their lack of reinforcement elements.

2.1. Innovative solution: Vertical anchors in combination with jet grouting columns

To overcome some of the above mentioned limitations, jet grouting techniques can be supplemented with vertical prestressed anchors. Jet grouting columns are applicable in a wide range of soils and can be executed under limited space and headroom conditions. The shape and arrangement of the jet grouting wall can be adjusted to suit the design and site requirements resulting in a highly versatile solution. One limitation being the requirement for multiple layers of ground anchors to resist the applied forces.

Design principle: Jet grouting walls without anchors (structural elements) are classified as gravity walls, the self-weight of the wall plays the most significant role in the support of the retained material. If anchors are incorporated in the retaining system, jet grout walls are then classified as composite retaining structures (Powrie, 2004). Design checks for jet grouting walls are identical to all other retaining structures with the exception for the internal stability of the wall. The failure mechanism is assessed by calculating and evaluating the line of thrust, which is defined as the locus of points through which the resulting forces pass in a retaining wall. To keep the structure stable, the position of the line must stay within certain limits. Depending on the design approach, these limits are defined by the core of the cross section for a conservative approach up to a limit dependant on the yield stress of the material. Put simply, the bending

capacity of a jet grout wall increases if the vertical stress inside the wall increases. This general behaviour is optimised with the combination of vertical prestressed anchors. The anchor head of the vertical anchor is placed at the top of the wall and when stressed the resultant force is acting as an external vertical force applied through the wall, this additional vertical force increases the internal vertical stress of the wall. The bond length of the anchor is situated either close to the bottom of the wall (System A, Fig. 1) or below the wall (System B, Fig. 1). System B is only possible if the soil below the wall is very stiff as this system also increases the stress of the material between the bottom of the wall and above the bond zone.

By utilising this solution both the required number of anchor layers as well as the required thickness of the jet grouting wall can be reduced. The vertical anchors can be installed after completion of the jet grouting columns and before the excavation starts, reducing the influence on the excavation sequence and providing scheduling advantages.

Figures 1 and 2 below show the cross section and analysis showing the resultant line of thrust for a site executed in Bratislava, Slovakia. In addition to the above mentioned advantages, this design enabled the advantage of providing a water tight structure and also avoided the need for anchors installed below the ground water table. This is a key consideration when confronted with soils of high permeability as any drilling below the ground water level is very difficult and risky.

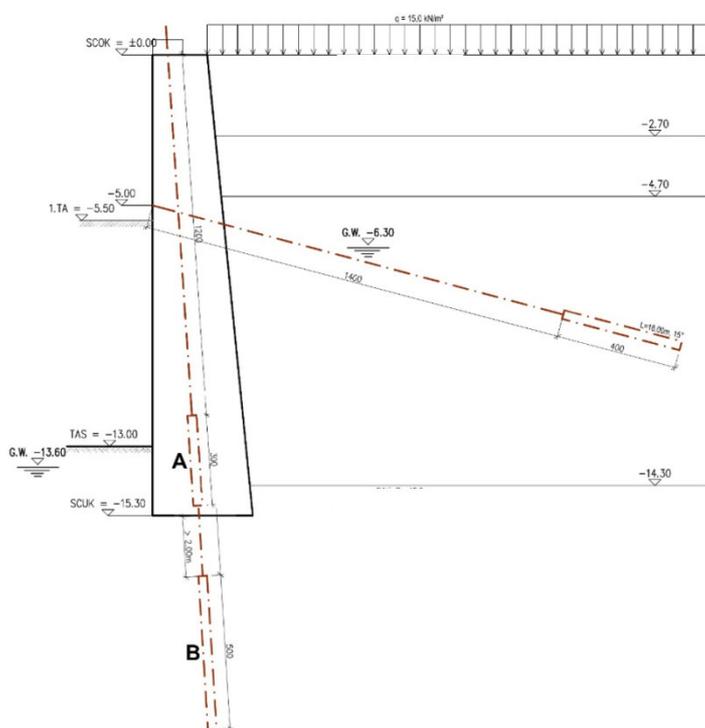


Figure 1: Cross section showing bond length of vertical anchor inside of jet grouting column (A) and below (B)

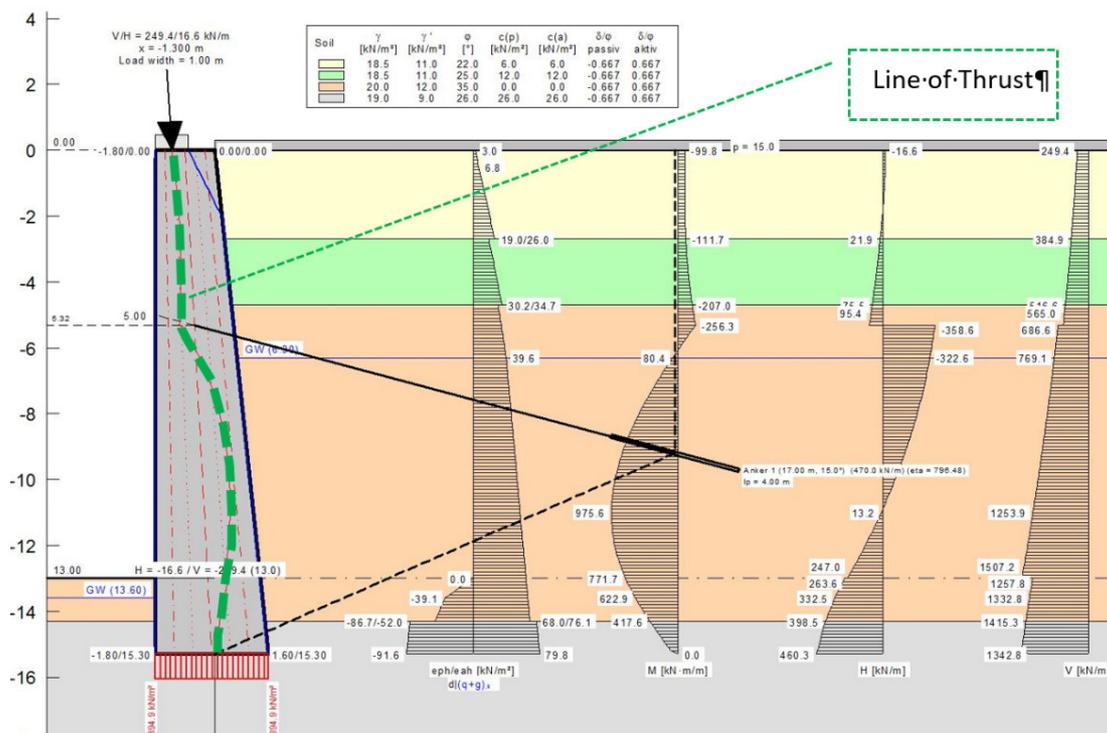


Figure 2: Model analysis of above shown cross section for case A (anchor within column)

A critical component of the system is the anchor head and its configuration. As the forces applied to the wall are comparably large in order provide a significant internal stress increase, the bearing of the anchor head must be capable of distributing the anchor force as homogeneously to the top of the wall as possible. Concrete blocks or beams are typically the most efficient solution. Evidenced below in Figure 3 is a bearing failure at the top of the column resulting from an insufficient bearing surface.



Figure 3: left: Poorly detailed anchor head; right: basement excavation with concrete anchor bearing caps/blocks

2.2. Innovative solution: Buttress walls

Another approach utilised in reducing the required number of anchors or ultimately avoid the requirement for anchors at all, is to consider a substantially thick wall. Such walls consist of multiple rows of columns which form a contiguous body. The design principle of buttress walls as opposed to a contiguous body is to omit columns from the second or subsequent row and rely on soil enclosed between the remaining columns to contribute sufficient mass to the stabilising unit. This results in a reduction to construction costs. To quantify the advantages of buttress walls Racansky (2008) investigated this design approach based on 3-dim Finite Element analysis (Figure 4).

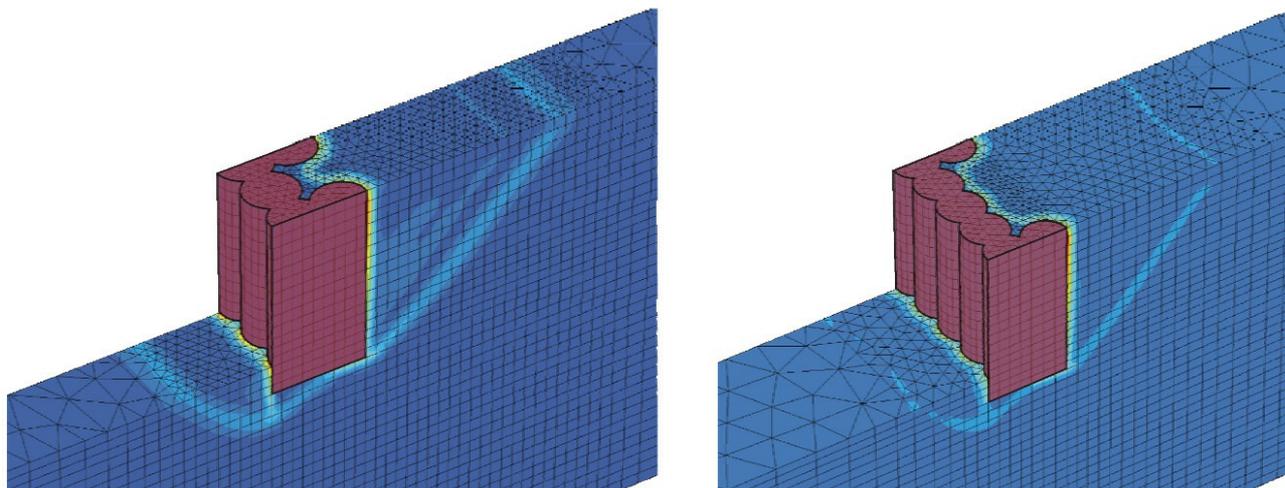


Figure 4: 3-dim Finite Element analysis to derive factor of safety

Analysis was undertaken for the extreme case of a continuous wall consisting of two rows of columns (S0). Several alternative but equivalent cases are shown in Figure 5) (S1-Sinf). As a result, by omitting every second column of the second row, the wall still performed close to the fully contiguous wall. A significant finding considering the treated volume has been substantially reduced. To simplify the design, diagrams with equivalent thicknesses based on the same factor of safety were developed, with the spacing of the buttresses dependant on the prevalent soil conditions. Buttress jet grouting walls have been particularly successful in Bratislava, Slovakia, as they perfectly complement the typical soil profile.

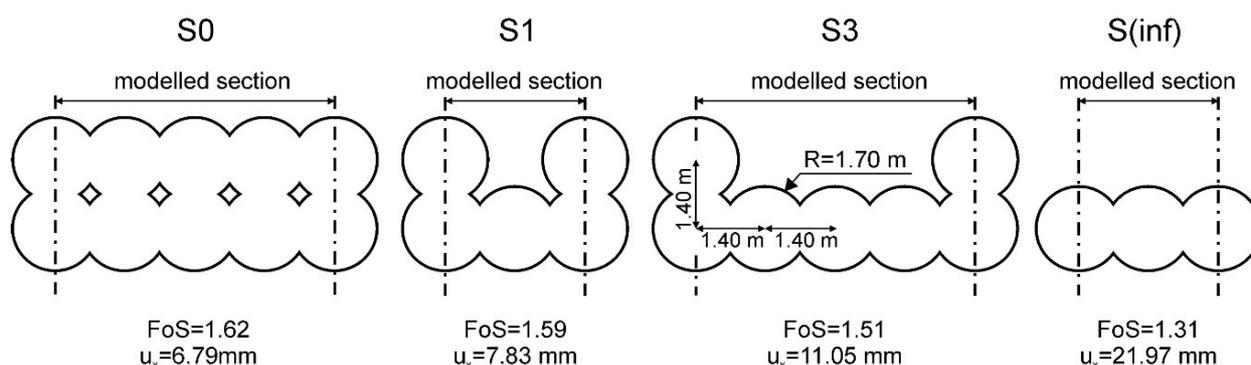


Figure 5: Analysed systems of jet grouting columns as Buttress Walls

3. CHALLENGING GEOLOGY

Some of the historical cities in Central Europe such as Vienna and Graz in Austria, or Prague, Czech Republic, have a particular soil profile providing significant challenges. Below an approximate 1 to 3m thick layer of fill or debris, there is a water bearing layer of quaternary sands and gravels up to 10m in thickness with tertiary stiff to solid silts forming the underlying layer. It is this lower layer of fines that makes the application of several techniques very difficult. The ability to penetrate with driven sheet piles into the stiff layer is very limited, and jet grouting, which is a common solution to treat the gravel layer, is limited by the achievable diameters within this lower layer. Piles, and in

larger projects also d-walls are applicable, however, cheaper and more versatile solutions are often required by the client.

3.1. Innovative solution: Layered solutions using combined products

Example of use: Close to the city centre of Prague a new building with several levels of basement had to be constructed. The excavation level reached several meters into the stiff silt formation. Due to very confined available space, applications requiring the use of large rigs and equipment were not possible – diaphragm-walls and bored piles. Therefore the designer had to utilise techniques that could be executed with comparably compact equipment.

Figure 6 below shows an overview of the multiple different elements used in the retaining system. Jet grouting walls were used to underpin the adjacent building and form a water tight sealing wall. The bottom of the jet grouting columns were designed to be within the transition zone to the stiff layer of fines. As the columns have no embedment, no horizontal stresses could be applied to the base of the columns. Therefore at least two layers of ground anchors or struts needed to be placed. Below the columns shotcrete and soil nails were designed to retain the silty layer. As the vertical stress at the base of the columns cannot be supported by the thin shotcrete layer, this would have resulted in a ground failure. To combat this failure mechanism additional micropiles were used to transfer the vertical loads of the columns deeper into the underlying strata bypassing the soilnail wall.

To understand the behaviour of such a complex retaining system, Finite Element analysis was used to create a very detailed model of all the structural elements and their reactions during each construction sequence (Figure 7). One of the significant advantages of the design was the ability to adjust it to all local variations, including the soil profile, loads and foundation levels of the adjacent buildings, and excavation levels.

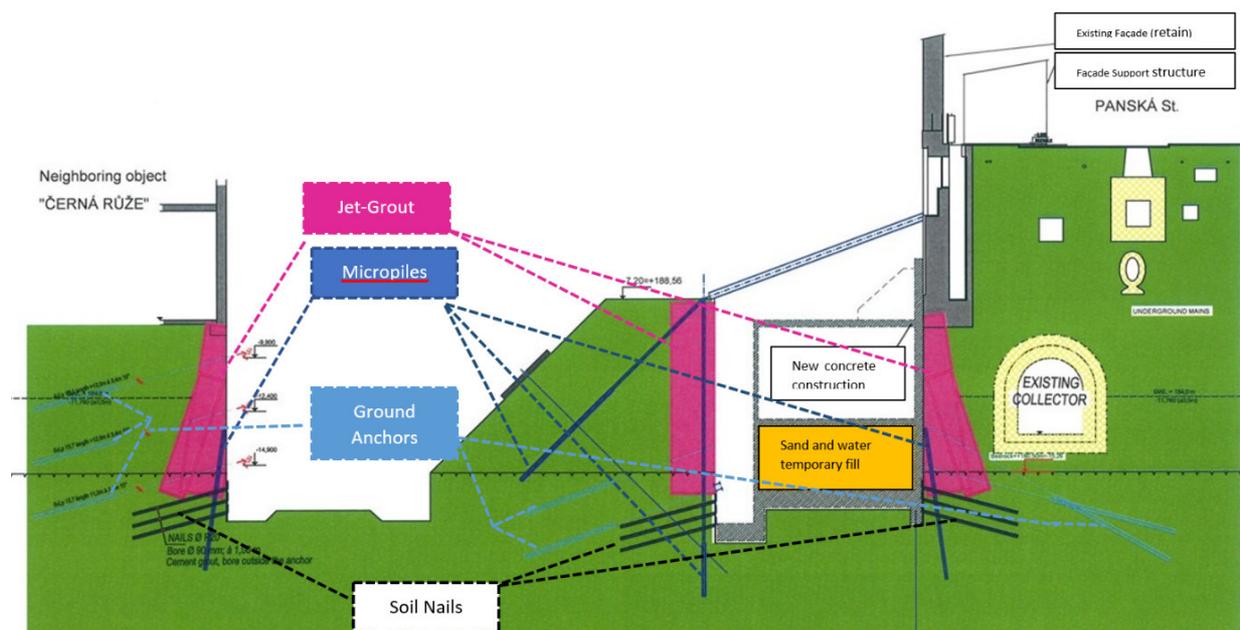


Figure 6: Cross section of site Na Příkopě, Prague

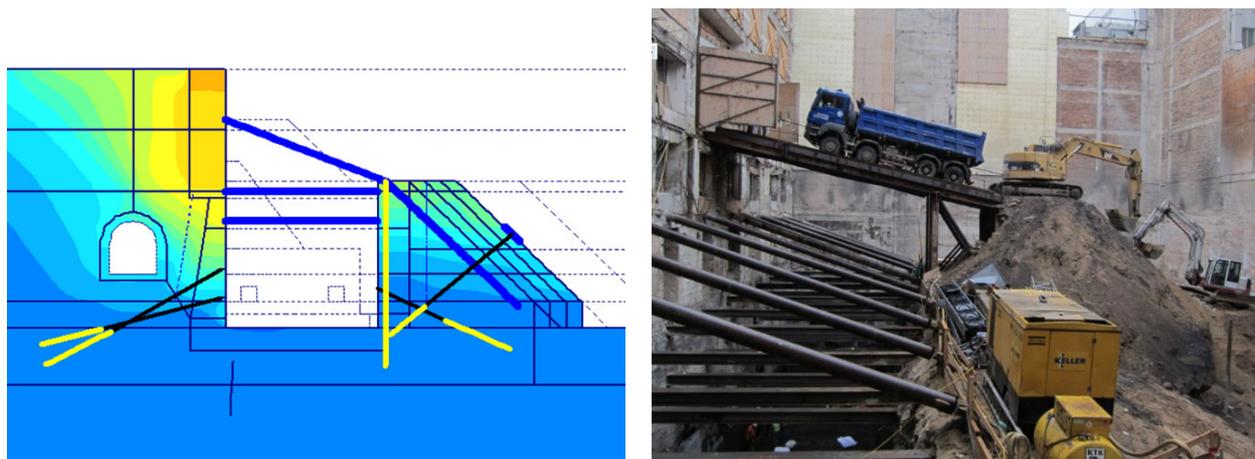


Figure 7: Comparison of Finite Element analysis (left) and execution (right)

4. WATER TIGHT RETAINING SYSTEMS

In many instances basement excavations extend below the ground water table. This results in the retaining structure having to resist not only the earth and water pressure but the additional requirement of forming water tight structure. One of the most commonly used systems is the hard-soft secant pile wall. From a design perspective this type of retaining construction is actually a split system, with the unreinforced primary piles prevent the water inflow between the secondary load bearing piles. These primary soft piles also distribute the earth and water pressure forces acting on them towards the stiffer reinforced secondary piles. However, much of the load distribution has already occurred behind the wall by means of arching effects within the soil.

4.1. Innovative solution: Contiguous pile wall with jet grouting sealing

When considering a secant pile wall, the designer is limited in choice of the pile spacing as it is a geometrical resultant of the pile diameter. Reinforcement within the secondary piles is determined by the loading conditions. If you consider a contiguous pile wall in place, this limitation is removed, therefore the spacing of piles can be selected in order to optimise the design. Generally this results in a more cost effective solution but creates its own issues with water ingress within the untreated/replaced soil between each pile. In this example the space remaining between the piles is filled with jet grouting columns that can be perfectly adjusted to suit the resultant spacing of the piles, again the flexibility of the getting solution is suited to rectification works on piles that have been installed outside of verticality requirements causing water inflow issues. Equivalent to the primary (soft) piles of a secant pile wall, the columns transfer the earth and water pressure to the secondary (hard) piles. During basement excavation, any protrusion of the jet grout column within the basement excavation can be easily trimmed. As these elements are not subjected to significant loads, the design can be further optimised by using semi (half) columns instead of full columns (Figure 8).

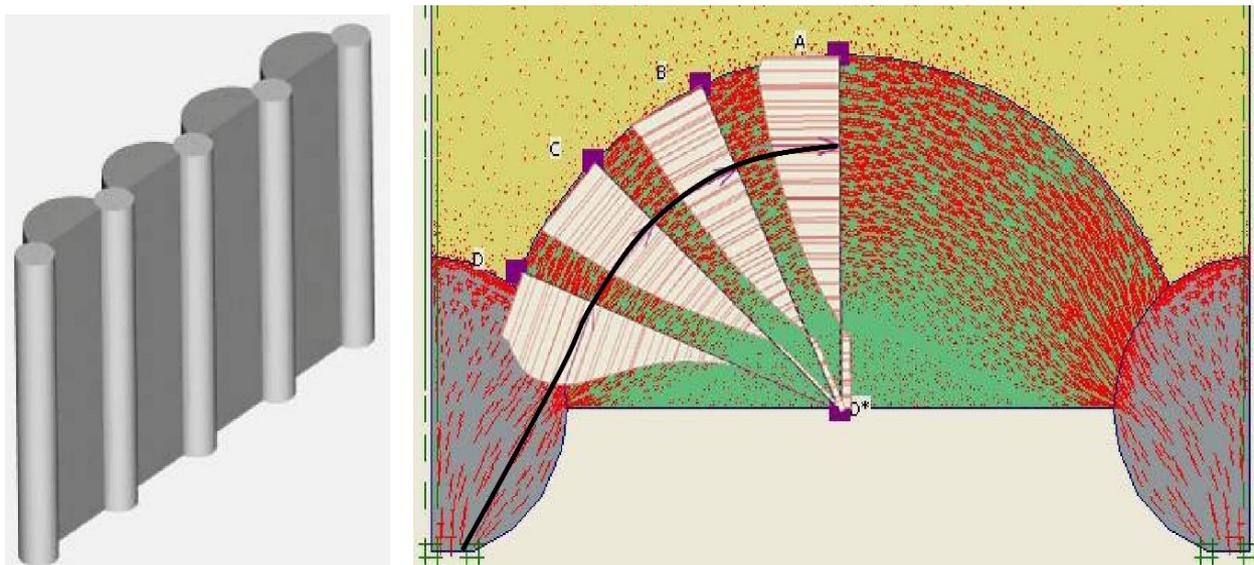


Figure 8: left: Jet grouting semi (half) columns between reinforced piles; right: normal stresses showing arching distribution

Design checks required for the columns are as follows: confirmation of the compressive strength of the jet grouting (soilmix) material and check of the shear stress at the interface to the pile. Stadlbauer (2010) analysed the stress distribution of various layouts, ranging from pile spacing similar to a secant pile walls up to larger spacing's of 3.0m. in which up to three jet grouting columns were modelled in between the secondary piles. Note: the secondary (hard) piles are installed as primaries when considering a jet-grout contiguous wall.

Figure 9 shows a design with two semi columns. As evidenced by the stress distribution and failure mechanism it can be determined that the critical component is the connection between the columns. The resultant arching mechanism passes very close to the edge of the columns, leading to local concentration of stresses. The phi/c-reduction of the Finite Element analysis (right picture in Figure 9) shows the shear stresses at failure. Moreover, Stadlbauer (2010) investigated the influence of geometrical imperfections of the initial column as well as pile position in combination with unfavourable inclinations.

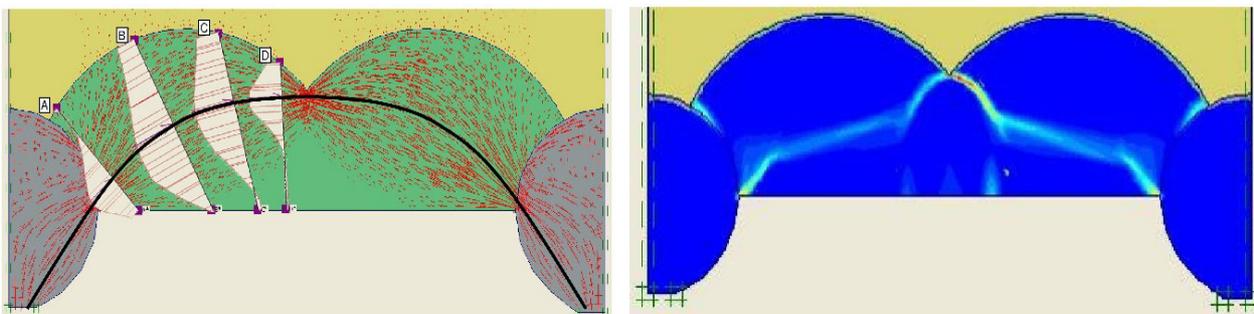


Figure 9: Application of two half columns; left: stress distribution; right: failure mechanism;

As an additional improvement full or semi columns can be substituted by thin jet grouting elements known as lamellas (Figure 10, left). With the installation of such thin elements the execution quality and quality management on site is extremely critical. Small deviations, especially for the direction of the lamellas, could result in the reduction of the contact area with the pile. Therefore, such systems are usually applied below the final excavation level.



Figure 10: left: jet grouting lamellas instead of half columns; right: trimmed jet grouting columns between piles

5. CONCLUSIONS

As new building sizes increase, and the available or usable space in cities decreases, the design of urban projects is becoming more and more complex. Quite often conventional solutions do not complement all boundary conditions or are simply too expensive. During the development of a solution, designers should be conscious that special geotechnical conditions within the project exist and it is important to have an understanding of available techniques and products, including their advantages, limitations, performances and cost. However, in-depth knowledge of all techniques is not universally available to many designers or consultants. Fortunately specialist geotechnical contractors can provide alternative or optimised solutions based on their experiences and knowledge, thus can add considerable value to the project as a whole.

6. REFERENCES

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