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Construction, design and measured performance of deep excavations

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ABSTRACT: This paper presents an overview of the papers submitted for the session on Construction, Design and Measured Performance of Deep Excavations, submitted for the proceedings of the Seventh International Symposium on Geotechnical Aspects of Underground Construction in Soft Ground, held from 16 to 18 May 2011 in Rome.

1 OVERVIEW

There are 22 papers within this session with authors from twelve countries: Italy, Germany, Holland, China, Greece, India, Korea, Malaysia, Poland, Russia and the United Kingdom. Authors of four of the papers are from academia, nine from industry and nine from a healthy mixture of both.

The papers have been broadly divided into four groups, although there is inevitably some overlap between groups. The first covers case studies with monitoring data and information on the design and construction of deep excavations. The second group relates to the study of deep excavations by numerical analyses. Several of the papers discuss issues concerning seepage, leakages and/or dewatering and these have been placed in a third group. The fourth group includes papers that describe ground improvement methods or new technologies for facilitating deep excavations.

2 DEEP EXCAVATION CASE STUDIES

In all deep excavation works it is necessary to estimate and try to control deformations, especially in the urban environment where existing structures and infrastructure need to be protected. Monitoring plays a key role in checking the expected outcomes from design and analysis, modifying these and ultimately checking and controlling the construction processes to minimise deformations.

All of the papers within this first grouping mention the monitoring that was performed and usually give some quantification of the displacements that were observed during the works.

The first paper considered, by Smits (2011), discussing the Rotterdam Randstad Rail project, sets the scene well within this context. The project involved 0.7 km of bored and 2.3 km of cut and cover tunnels and deep excavations supported using diaphragm walls. Ground improvement techniques, such as in-place soil mixing, jet grouting, ground replacement and ground freezing, were implemented within the soft Holocene soils encountered. As the new construction would potentially affect a number of existing structures and services a risk management system was set up involving hazard levels. The integrated monitoring and risk management system for the construction works is described and discussed with examples in the context of protecting the 'surroundings', adjusting the monitoring system and anticipating the finances that might be required as part of implementing mitigation measures.

The control of ground and structural displacements can frequently be controlled by adopting more substantial (and expensive) construction techniques. The paper by Wang and Xu (2011) provides a very extensive coverage of the construction techniques adopted for many deep excavations in Shanghai during the past two decades. The geotechnical ground conditions are described initially—in doing this the reader immediately understands the challenges of constructing within the extensive depths of very soft recent soils. Figure 1, from the paper, showing a bird's-eye view of part of the city, highlights the density of very large and high structures that need to be protected during underground works. The paper is very valuable as it collates a wide scope of methods for constructing retaining walls (see Fig. 2), lateral and vertical support systems with clear and helpful sketches and photographs and discussion on their benefits and limitations. It goes on to describe a number of benchmark deep excavations in Shanghai, e.g. the largest and deepest deep excavation, the largest circular excavation. In order to control deformations approaches such as performance-based design and practical construction methodologies are described and discussed, such as top-down method, advanced reinforcing soils within the excavation area and adopting zoned excavations.

The authors, Pagotto, Silvi and Casadei (2011), of the paper 'Underground car parks in Italian urban areas—not an easy task!' are also very familiar with the various issues of constructing deep circular excavations for car parking in the urban environment. They give a comprehensive breakdown of a number of practical items to consider, ranging from interaction with the neighbours, assessing the condition of the adjacent structures through to facilitating archaeological investigations. They also stress the importance of subsurface services, saying that in some cases the cost of dealing with these precludes financially the excavation going ahead. Technical issues are then dealt with including ground conditions (with seismic considerations in Italy), modelling loads, checking pile position and the need for corrective measures and waterproofing. New construction methods are also briefly described and their advantages discussed.

Figure 1. A birds-eye view of part of Shanghai city showing numerous skyscrapers (from Wang and Xu).

Moving back to the Netherlands, Everaars, Kwast, Meulblok, Delfgaauw and Mortier (2011) describe a project currently underway to provide a new cut-and-cover railway tunnel and station in the city of Delft. Of particular interest is the fact that the diaphragm walls which support the excavation for the tunnel and station have also been designed to carry the vertical loads of a new city hall to be built above them. They also need to be impermeable. The diaphragm walls in certain areas have such large bending moments that it was not possible to provide sufficient gaps between the necessary reinforcing steel. Trials were performed using shallow diaphragm wall shaped excavations to assess the optimal concrete mixture and casting method. High vertical loads and the potential for differential settlement were overcome by adopting spreading beams at the top of the diaphragm walls and barrettes in conjunction with varying their toe levels. An important consideration raised by the authors is the need to check the integrity of the diaphragm wall joints to avoid leakages and the consequent risks associated with them. This subject is dealt with later in this session (papers by Vanni and Geutebrűck, 2011 and Spruit *et al.* 2011).

Meissner, Quick, Michael and Arslan (2011) describe the challenges of constructing the foundations for a 200 m high tower block T185 in Frankfurt. A piled-raft solution was selected with a combination of diaphragm and secant-pile retaining walls supporting the walls of the two levels of basement. Advantages of using a piled-raft foundation are given, an important one

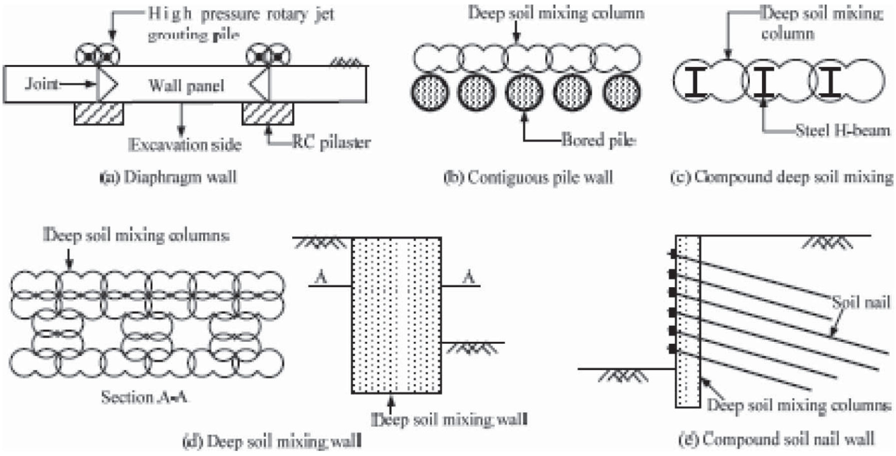

Figure 2. Sketches showing some typical retaining wall types used in Shanghai (from Wang and Xu).

being the reduction of settlements and differential settlements. An optimised foundation design was achieved using 3-D finite element analysis. Measurements of settlements and wall head displacements relating to the stage of construction at the time of writing, corresponded well with calculated values. The latter were greatly reduced (only ~5 mm) where inclined struts were adopted in the vicinity of an existing subway line.

Three case studies from St Petersburg, Russia involving deep excavations are described by Mangushev, Lashkova, Smolenkov and Osokin (2011). The soils are weak, sensitive, they occasionally contain boulders and often have high water tables. Each of the three cases involved excavations deeper than 12 m and involved the use of sheet piles, sometimes semi-circular in section and sometimes installed within a cement-clay solution, subsequently replaced by concrete—to provide what is termed 'wall-in-the-ground' structures. In all cases it was necessary to install piles to prevent base uplift. Generally the deformations of the walls were deemed acceptable and adjacent structures were not damaged—in some cases these buildings had their foundations reinforced by Titan piles—there is an interesting contrast in the Stockmann trade centre case where one building that was not reinforced in this way required some subsequent restoration work.

Deep excavations in the urban environment where there are nearby structures that need protecting is often achieved using diaphragm walls. Predicting the lateral displacements of these walls is an important component of assessing potential building damage. To achieve this, the geology needs to be understood and representative soil parameters are required for numerical analysis. In many instances this is not possible, e.g. where the geology changes rapidly. Back-analyses of monitored wall movements provides a method of quantifying displacements in complex ground conditions. Siemińska-Lewan-dowska, Mitew-Czajewska and Tomczak (2011) present data from 18 case studies involving diaphragm walls providing a useful range of typical movements for the various ground conditions encountered in Warsaw. The case studies have been divided into three groups involving different construction methods with: (i) anchors, (ii) props and (iii) top-down construction, illustrating typical ranges of movement to expect with different soil conditions under controlled construction procedures.

Challenging groundwater conditions in the very close proximity of the sea had to be overcome in order to construct the two-level basement for a major hotel complex in Tripoli, Libya. The paper by Asioli, Agostini and Minotti (2011) describes the approach used to control the ground water flow into the excavation (through permeable soils), designed in conjunction with consideration of the diaphragm wall depth. Another important consideration was to keep the water level outside the excavation as high as possible to avoid damage to nearby structures. Preliminary numerical analyses were performed to assess the best approach to construct the excavation considering three scenarios. This illustrated that increasing the depth of the diaphragm walls did not provide much additional benefit and that it was best to pump from within the excavation. More detailed numerical analyses were then performed to design the walls, accounting for local and global stability and the anchors used and the dewatering system. The project was successfully completed in good time, illustrating the effectiveness of the design and good teamwork between the parties involved.

The effect of staged dewatering in conjunction with staged top-down excavation is discussed by Zheng and Li (2011) who provide monitoring data from a deep excavation in Tianjin, China (see Fig. 3). They explain how the staged construction processes result in an increase in effective stresses in the silty clay and silts present at the site, thus reducing the compressibility of the soils and reducing the heave of the soil at the base of the excavation. They back up their hypothesis using

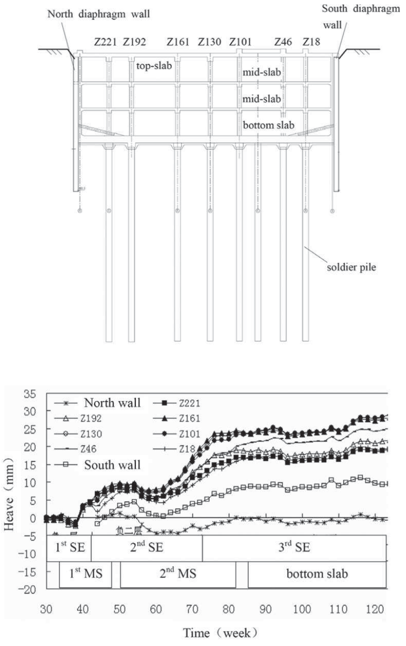

Figure 3. Profile of excavation using top-down construction and monitoring date showing heave of diaphragm walls and piles (n.b. SE = staged excavation, MS = mid-span construction) (from Zheng and Li).

triaxial tests performed following stress paths simulating the anticipated ground response during construction at points close to and away from the diaphragm walls. The monitoring data presented can be interpreted within the framework of their hypothesis and experimental results. The paper therefore emphasises the importance of taking staged construction into account.

3 STUDY OF DEEP EXCAVATIONS BY NUMERICAL ANALYSES

The complex soil-structure interaction processes involved with deep excavations and often their three-dimensional nature mean that for most cases the only way to predict and understand the mechanisms taking place is to perform sophisticated numerical analyses.

Numerical analyses have been used more and more in recent years with increased computing power, improved numerical techniques and more comprehensive constitutive models. Great care is required in such analyses along with a fundamental understanding of the soils, the constitutive models and the analyses themselves. It also has to be remembered that the more complex the constitutive model, generally the more soil parameters that are required, necessitating extensive sophisticated laboratory test programmes.

Three papers are included in this section. They provide comprehensive details about analyses performed to model the construction of deep basements. They also contain details about construction methods and present monitoring data for comparison.

In the paper by Becker, Berhane and Kempfert (2011) numerical back-analysis has been used to investigate the effects of factors such as construction and excavation stages on the deformations of a secant-pile wall supporting a 5.9 m deep excavation in soft lacustrine clays. The development of the measured displacements and pore water pressure changes are compared with results from the 2-D finite element analysis which accounts for the use of a waling beam cast around the inner perimeter of the top of the wall and the sequence of excavation steps (Fig. 4).

In particular the progressive mobilisation of the different support measures (walls, steel props and base slab) is considered with the developing displacements. An important factor accounted for is the anticipated stress path followed during the construction (similar to the paper just described by Zheng and Li)—the ground has been spilt into different zones subjected to a variety of stress paths as indicated in Figure 5. The comparison between the measured and calculated displacements indicates the improvement of the analysis when the appropriate stress path is considered.

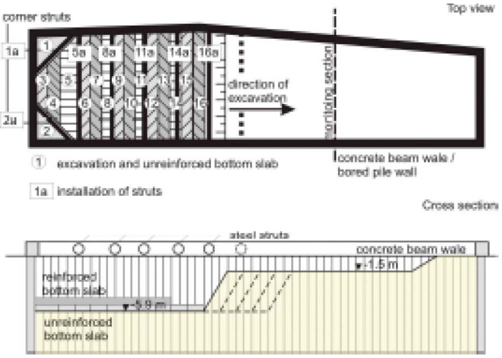

Figure 4. Top view and cross-section of excavation site with idealized construction stages (from Becker *et al.*).

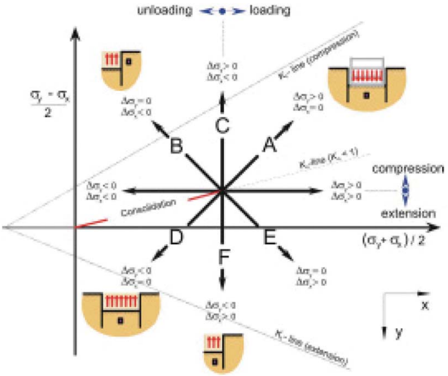

Figure 5. Idealized stress paths for triaxial tests (from Becker *et al.*).

A numerical analysis using the finite difference approach was implemented to help with the design of protective measures during the excavation of a 12 m deep four-level basement for parking adjacent to an existing building in Thessaloniki, Greece. Comodromos and Papadopoulou (2011) report that the existing building started to move unacceptably during demolition of the building that previously occupied the site. Attempts were made to underpin the existing building using jet-grouting but the ground (primarily sands and gravels) was so weak that the stress relief that took place prior to the grout hardening caused further movements and rotations.

A different approach using a curtain wall of steel tubes beneath the existing foundation was investigated (see Fig. 6) and designed using the analysis and all stages of the subsequent works were also modelled. The plane-strain analysis indicated that

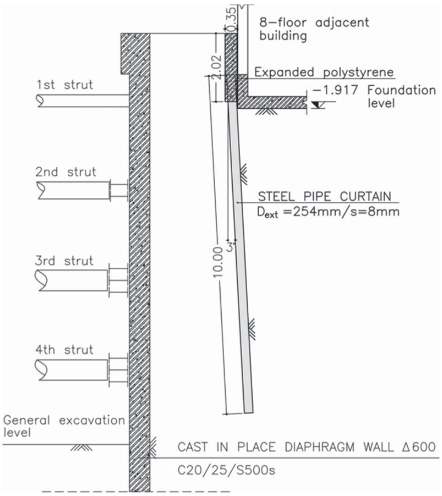

Figure 6. Support measures used to protect building prior to adjacent excavation (from Comodromos and Papadopoulou).

the curtain wall would reduce displacements and rotations and that to minimise them further the steel props should be prestressed with 500 kN. There was good agreement between the horizontal displacement measured at the top of the adjacent building with that predicted.

Furlani, Guiducci, Lucarelli, Carrettucci and Sorge (2011) describe the construction processes used to sink two large shafts (15.7 m inner diameter) about 5 m apart and 45 m deep forming part of the Metro C works in Rome. The shafts acted as TBM reception chambers and were then incorporated into the metro system for ventilation. They were sunk in complex ground conditions comprising strata of volcanic formation, altered tuffs and pyroclastic materials. A particular concern was the medium to high permeability of the strata as the base of the excavation was 24 m below the water table. This was dealt with by grouting the base of the diaphragm walls to create a zone in the form of an inverted arch. Comprehensive 3-D numerical finite element analyses with advanced constitutive models were used to assess effects such as the interaction of the shafts, the effects of ground treatment in the vicinity of the openings for the TBMs and the stress redistribution once the TBMs broke through. The analyses revealed that the latter process was the most critical structurally for the shafts themselves. Monitoring showed that the grouted base of the shafts worked well and that ground movements associated with TBM works were greatest, those from shaft construction being negligible.

4 STUDIES RELATED TO SEEPAGE, DEWATERING AND LEAKAGE

In any deep excavation, water ingress into the excavation and the potential destabilising effects water has on both the retaining walls and the base are all major concerns to anticipate. The papers discussed so far—in particular the paper just described by Furlani *et al.*—all allude to some degree to the subject of water ingress, while it is the main focus of the following papers within this group.

The very complex stratigraphy of Rome and its effect on the distribution of permeability values is described and discussed by Grisolia, Iorio and Zechini (2011) with particular reference to the dewatering works for the three stations Teano, Mirti and Gardenie along the Metro Line C. The stratigraphy of the beds is frequently not continuous and the range of permeabilities as established from LeFranc tests spans five orders of magnitude (10^{-8} to 10^{-3} m/sec).

Dewatering field tests were performed to compare with estimated pumping rates necessary and in two of the stations (Mirti and Gardenie) the rate of pumping was much greater than expected and it was still not possible to draw down the water level within the station boxes themselves to adequate levels (comparisons were made between water conditions within and outside of the excavations). Reasons for these differences are identified from seepage flow analysis as being due to different flow regimes within the strata and around the walls. In order to reduce the flow in the two stations, grout curtains were installed (using the same technology as described by Furlani *et al.* 2011). A 2-D numerical steady-state flow analysis was performed to compare average permeability values within the strata before and after grouting, using pumping rates to calibrate the values. It is felt by the authors that these analyses were more useful than the LeFranc tests for the complex ground conditions encountered. The grout curtains worked well in reducing permeability value.

Still considering the Line C of the Rome Metro Line C, Capata and Capata (2011) provide further information about the groundwater conditions beneath Rome, this time considering the Malatesta shaft. Again the complex stratigraphy is described but there is more emphasis in this paper on the design of the wells themselves considering their depth, diameter and spacing. Dewatering trials were performed—an essential exercise when the ground conditions are so complex and varied. Two water table depths were confirmed separated by a low permeability silty layer. In this case study the pumping tests indicated that the diaphragm walls penetrated into substantially impermeable strata and that they were themselves well constructed. Comparisons are made with the experience from the Gardenie station (discussed in the previous paper by Grisolia *et al*. 2011) where the extent of the fractured tuff was such that it was not completely sealed by the diaphragm walls, hence requiring the installation of a grout wall to reduce permeability values and flow rates.

In the next paper considered in this group we move further south in Italy to the coastal city of Bari. Granata, Gioia and Cotecchia (2011) describe the geology of the area which comprises primarily 'Bari Limestone' which extends to great depths and comprises sequences of limestone, dolomitic limestone and dolomite. Comprehensive ground investigations were performed to establish hydrogeological and geomechanical conditions. Of significance is the frequently karstic and open-fractured nature of the Bari Limestone (permeability at the site was established as 10^{-4} to 10^{-3} m/sec). The excavation was to extend to 7 m below the natural ground water level. The geotechnical characteristics of the limestone were also estimated for assessing, using numerical analysis, the stability of the excavation during and on completion of the works. Detailed information is given about the grouts and grouting operations that were implemented to reduce the permeability of the strata both within and beneath and around the perimeter of the excavation. Three grout mixes were used, selected to suit the nature of the fracturing and voids and the grouting operation sequences. The grouting very effectively reduced the overall permeability of the ground with an average value being estimated as about 10^{-7} m/sec. Following these operations the excavation was completed successfully under safe and dry conditions and no damage to the adjacent historic buildings is reported.

The next two papers in this group discuss methods of detecting leaks and imperfections in diaphragm walls. Clearly this would be of great benefit to establish before excavating.

Vanni and Geutebrűck (2011) explain a new technology for detecting leaks and provide a case study where it was used. The method works by measuring ion flow within electrical fields. A series of sensors are placed within the excavation area, set out in a grid arrangement and in the case study pairs of boreholes outside and within the excavation were used to induce flow of artificial electrical tracers (see Fig. 7). The sensors detect where there is greater flow and hence potential points where leakages through the diaphragm wall may be occurring. The case study is the Gondar station on the new Line B1 of the Rome Metro. It was realised during construction that instrumentation within the hydromill was faulty during construction of certain panels and the 'multi sensor leak detection' technology was used to confirm the exact location. It was able to show competent areas and allow grouting works to be carried out inside and outside the retaining walls prior to excavation works. Excavation of the station box was subsequently completed without any leakage problems. Such technology clearly has a very important role in such cases from viewpoints of stability during excavation, safeguarding of nearby structures and significant cost savings. The second paper covering the issue of leaks and imperfections in diaphragm walls is by Spruit, Hopman and van Tol (2011) who report on investigations using four techniques applied to a full-scale constructed wall and smaller-scale panels cast in a laboratory environment. Temperature was monitored and found to have most benefit during the bentonite replacement and concrete casting stages, allowing potential defects to be identified during production. Natural gamma radiation measurements were found to have only limited

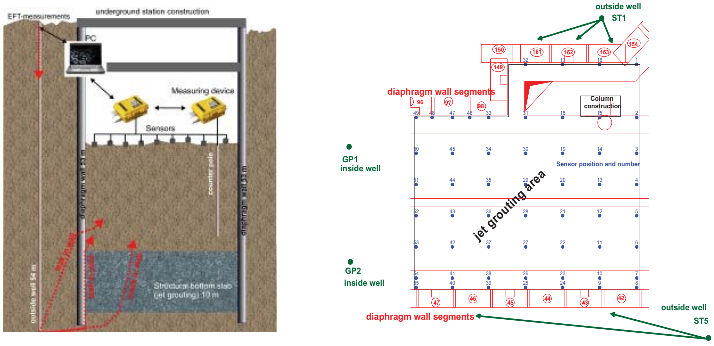

Figure 7. Schematic illustration of the leak detection method for deep structures and the sensor grid map for Gondar station with 55 sensors outside EFT-energy wells and inside counter poles on excavation level (from Vanni and Geutebrűck).

application for the case studied. Cross-hole seismic tomography was found to be efficient: tubes are required within the panels but these allow defects within the joints to be detected (where they occur most frequently). The fourth approach involved measuring electrical resistivity and this indicated an anomaly at the same location as the previous (CHST) method. It proved more efficient to use the full-scale panels for assessing the methods and confirmation of what was detected will be possible during excavation within the volume enclosed by the diaphragm walls. Therefore what is presented in this paper constitutes a class-A prediction!

5 GROUND IMPROVEMENT METHODS AND NEW TECHNOLOGIES FOR FACILITATING DEEP EXCAVATIONS

In this final section four papers covering quite different topics have been grouped as they all broadly relate to ground improvement.

Jet grouting is sometimes adopted for the improvement of the ground for tunnelling and deep excavations. However, there are sometimes uncertainties about how to control the effectiveness of such works. Eramo, Modoni and Arroyo (2011) explain the approaches that are available for controlling uncertainties in design and optimising site operations. In some cases the control is by specifying diameter, unit weight and strength of columns while an alternative is to focus on field trials. A case study from Barcelona is described where a base plug for a large excavation to form a station box was formed using jet grouting. A number of field trials were performed using different jet-grouting systems and these were assessed in a variety of ways (rotary coring and testing of samples etc) to define the best technique to adopt. A statistical analysis was used to facilitate the assessment of the results. Ground surface movements were also monitored, which allowed some significant settlements to be identified for certain grouting systems (in particular it was found that systems where large amounts of cement were injected resulted in large settlements). The field trials and monitoring thus allowed the jet-grouting method to be optimised and adverse effects, such as settlement, to be minimised using a rational and objective procedure.

A new technology involving 'Cutter-Soil-Mixing' (CSM) is described by Gerressen and Vohs (2011) who say that it offers an alternative to jet-grouting. The method of deep mixing uses rotating cutting/mixing elements that rotate about a horizontal rather than the usual vertical axis (see Fig. 8). Details are given concerning the construction steps and the range of sizes that can be dealt with. Comparisons are made with other techniques and a number of advantages to the new system are highlighted. Various case studies are then presented to illustrate the application of the system, i.e. for retaining walls, foundations and soil improvement. It seems that there is potentially a great diversity of applications that can be achieved with the CSM to considerable depths requiring less space for the plant.

Figure 8. Mixing wheels and housing for hydraulic gear drives of a CSM unit (from Gerressen and Vohs).

Another technology, developed within the oil industry and now applied to geotechnical engineering challenges, is directional drilling. Vanni, Siepi, Croce, Melli and Specchio (2011) describe historic uses of such a technology and then go on to describe some new applications, illustrating them with case studies. The previous uses were to allow pipelines to be installed beneath urban areas or rivers where open-cut excavations were not practicable or to implement compensation grouting without the need to construct shafts from which to install the TAMs and inject the grout. They then describe two case studies where directional drilling was used to repair two dams (in New Zealand and the US) by constructing cut-off walls. A particularly challenging application involved containment of contaminated ground at two sites in Italy. It was discovered that there was no base protective membrane at the base of the contaminated ground. The ground could be effectively sealed using walls but initially it seemed that the only way to seal the base was to remove the contaminated material, install an appropriate membrane and then replace it. The new approach allowed the underlying calcarenite to be grouted, thus sealing off any potentially harmful leachates without having to disturb the waste material (see Fig. 9).

Anchors are often used in earth-retaining structures to increase stability and reduce deformations.

value calcium silicate hydrate crystals are formed

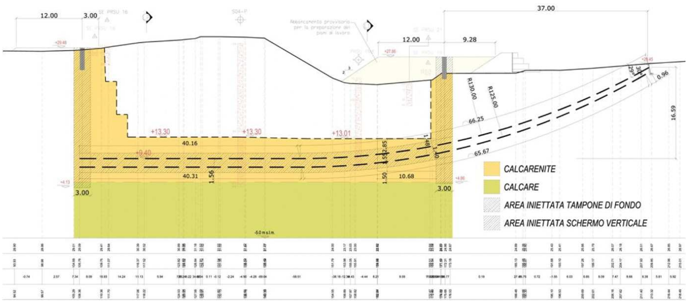

Figure 9. Base slab construction, allowing contaminated ground above to be sealed (from Vanni *et al.*).

The effect of pressurised grouting of compression anchors in residual soils has been investigated and is reported by Kim, Sim, Kim, Lee and Lee (2011). They describe a study involving (i) cavity expansion theory, with and without incorporating the permeation characteristics of the grout; (ii) laboratory small-scale model studies and (iii) field tests. Three residual soils commonly found in Korea were investigated. Using and comparing the results from these three lines of study, the authors conclude that the grout penetration should be used in conjunction with the cavity expansion theory when the ground permeability is greater than 10^{-5} m/sec. Increases in ultimate pull-out resistance can be gained for weaker soils for which SPT values are less than 50 but there is little benefit for stronger soils. It is suggested that the results could be applied to other residual soils.

The final paper within this session under the heading of ground improvement, by Kazemain, Prasad and Huat (2011), discusses the effect of cement on tropical peat from Malaysia stabilised by deep mixing. Three peat types were investigated: fibrous, hemic and sapric which have reducing water contents (~505%, 325% and 190% respectively), organic contents and fibre contents. Samples were prepared, with a central core of cement-mixed soil, which were then left submerged for 28 days to cure and then tested in Rowe cells to investigate the effect of cement content on primary and secondary compression characteristics (C_c and C_α). These tests were supplemented by microstructural studies using an SEM. All three types of peat showed a reduction in compressibility (C_c and C_α) with increasing cement content. Calcium and hydroxide ions are generated during the cement hydration process and when their concentration reaches a certain threshold value calcium silicate hydrate crystals are formed which bond soil particles and increase shear strength. The SEM analyses confirmed this effect and showed that it occurred most beneficially in the sapric peat.

6 CONCLUSIONS

The papers within this session have provided some excellent examples of field data, construction technology and design and analysis. The use of numerical analysis to understand how loads and stresses are redistributed in and around deep excavations and the resulting deformations that occur continues to increase in popularity. Field monitoring plays an essential role in validating the results from such analyses and controlling the works during excavation/construction. There are a number of excellent examples within this session illustrating this approach.

There is still an important need to try to make sure that published papers providing monitoring data include sufficient additional information to allow readers to use the data to validate their own independent numerical analyses. Defining the scope of information that is typically required to achieve this is the goal of one of TC204's Working Groups. Another closely linked Working Group is involved with the creation of a database where such information can be stored, again trying to make sure that sufficient information is provided. Details concerning both of these working group activities can be found on the TC204 website.

Some of the papers provide very useful statistical information about the effectiveness of various construction techniques, along with typical ranges of wall deflections etc—the papers by Wang and Xu (2011) and Siemińska-Lewandowska *et al.* (2011) are good examples.

In terms of construction technology, there are two papers that deal with the important topic of leaks through diaphragm walls. There are a number of case studies reported in the literature where such leaks have caused serious problems. The papers by Vanni and Geutebrűck (2011) and Spruit *et al.* (2011) discuss new techniques to detect such leaks and cite case studies where different approaches have been used.

This concludes the general report on papers grouped under the heading of 'Construction, design and measured performance of deep excavations'. Readers are encouraged to read the individual papers within the proceedings for more detailed information and references.

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