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Innovations to support developments of infrastructure for mega-cities
Des innovations en soutien du développement d'infrastructures pour les mégapoles

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ABSTRACT: Geotechnical innovations, in the form of improvements of already established technologies and processes, as well as implementation of advanced products and procedures play a decisive role in mastering the current and future geotechnical challenges to prepare the infrastructure for the requirements of urban conglomerations. With increasing complexity of projects for upgrading our infrastructure to meet the future requirements of mega regions, geotechnical innovations can be an opportunity to meet goals. The examples show the innovative procedure of combining advanced technologies demonstrating the advantages gained employing a advanced technology in combination with advanced design. The conclusions summarize the preconditions to identify and realize innovative solutions and the minimum management and organisational structures required to successfully integrate innovations into geotechnical processes and the market to the benefit of all.

RÉSUMÉ: Les innovations géotechniques sont appelées à tenir un rôle prépondérant dans la maîtrise des défis présents et futurs pour la réalisations des infrastructures nécessaires au développement des mégapoles. Il s'agira de l'amélioration de techniques déjà existantes aussi bien que de la mise en peuvre de technologies et produits nouveaux. Avec la complexité croissante des projets nécessaires à l'amélioration de nos infrastructures pour satisfaire les besoins des méga-regions, les innovations géotechniques représentent une opportunité d'atteindre avec succès. L'exemples met en avant une combinaison innovante de techniques et de calculs aux éléments finis. En conclusion, sont passées en revue les conditions préalables à l'identification et à la mise en oeuvre de solutions novatrices, ainsi que les schémas structurels requis pour une intégration réussie des innovations géotechniques afin que le marché en retire tous les avantages.

Keywords: Innovations, GeoBIM, DSM, cased deep mixing, advanced design

1 CURRENT MARKET CONDITIONS AND TRENDS

The past financial crisis in the western world and the efforts not only to consolidate national budgets, but also to rescue certain banks, have not left the building industry unaffected. Some drastic cutbacks to public budgets, along with the increasingly restrictive granting of credit for the financing of construction projects, have left enormous over-capacities in the construction sector, with purely negative impacts. As a consequence of these negative developments, many companies experienced the pressure to restructure more quickly and to reduce costs, but at the same time to keep the consequences of all activities, both externally and internally, within limits acceptable to employees, owners and finance institutions and, last but not least, for their costumers. The construction industry was not only undergoing substantial changes because of these basic alterations in the global conditions; the following additional transformations will influence development during the coming decades:

- Acceleration in globalisation must be reckoned with, with the economic output of developing countries growing about 3 times faster than those of the industrial nations,
- Mega centres of the world will continue to attract more workers and infrastructure problems will accompany the corresponding development.
- Energy requirements will increase dramatically and require a more efficient and stable infrastructure.

These future changes in the basic conditions will also force construction organisations to change in order to remain competitive. Attempts to work under these conditions both competitively and cost-efficiently are limited and, in many cases, result in a pure competition on costs. But apart from the **cost** factor determined by effectiveness and better efficiency, competitiveness is, in addition, influenced by the following parameters:

- **Quality:** experience and capabilities of employees, training and further training, as well as management abilities.
- **Time:** influenced by productivity and advanced technology.
- **Innovation:** in the form of product and/or process innovations.

A business can best cope with transformations and changes in progress by improving its own competitiveness through innovative approaches. The influencing factor of innovation offers the largest possibilities for increasing competitiveness and attaining competition advantage through new, innovative ideas.

2 FUTURE CHALLENGES IN CONSTRUCTION

The environment described above clearly shows the ever-changing nature of tasks, particularly in the geotechnical sector, with changes in customer needs as guidance. The significant challenges in the geotechnical world can be summarized as:

a. **Construction projects are becoming more and more complex:** The increasing complexity of projects will lead to significantly more attention being paid to experience and competence in such tasks as planning, designing, cost estimation and execution. Only by integrating all these levels of competence into the innovation process will the complexity be manageable.

b. **Economic optimization requirements will promote global co-operation and increasing global competition:** In the future, due to more and more global competition from low cost regions, optimizations for economic improvements will create substantial cost pressure and will force cooperation. These developments will create increasing international competition and, with increasing internationalization of the market conditions, intensified contractual conditions and clauses. To cope with this challenge, extended knowledge of contract and risk management will be essential, alongside the increasing requirement for technical innovations to stay competetive.

c. **Increasing demand for automation and the automatic monitoring of building processes:** With increasing complexity and increasing pressure on efficiency, automation and the automatic monitoring of building processes will become increasingly important to maintain the required standard of quality. A significant innovatoin task for the future will be to minimize risks of faults, to bridge as many gaps in experience as necessary, and to avoid negative consequences. But automation will create new requirements, on device manufacturers and suppliers in particular, to directly and promptly optimize productivity and quality using improved, process-oriented monitoring in the construction process.

d. **Clients and consultants will expect more efficient documentation of the processes and quality:** Increasing requirements for documentation of construction processes will inevitably lead to improvements in existing quality and risk management systems, to be developed in parallel with the requirements for automation. An even closer cooperation between users and manufacturers of construction equipment will, in most cases, be adapted as counteraction to these future tasks for process cycle documentation by using measuring and sensor technology.

e. **Environmentally-friendly technologies are becoming more attractive:** The development and advancement of resource saving technologies and building processes will become a significant challenge for the entire construction industry, but particularly for geo-technologies. Alongside the reduction in the consumption of materials and emissions (noise, dust, vibration…), of CO2 emissions in parallel to the reduction of energy consumption and also the improvement of logistic processes will be at the forefront.

Considering all these future challenges as general requirements to the different construction processes, innovative solutions, as a combination of alternative products, alternative designs, alternative materials and alternative execution procedures, could show a way out of this problematic issue.

3 INNOVATION AND BUILDING PRACTICE

Innovations, whether improvements to products or procedures, are naturally subject to technical codes and standards that generally must and be fulfilled. An innovation usually involves an increase in complexity, and thus leads to higher risk levels with warranty entitlements increasing at the same time.

Innovations require more investments in crosschecks and quality assessment, in addition to faster implementation cycles (time to market) (Wehr, Topolnicki, Sondermann, 2013).

To maintain competitiveness over a longer period of time, constant innovation and the improvement of existing products are basic requirements. In addition, each innovation must, above all, deliver an increase in value for the customer in terms of costs, quality and/or time. Only if and when an innovation fulfils this complementary condition of creating an added value for the customer, can it also succeed in competition. Innovative ideas are not easy to identify; reviews of innovative processes and products disclose that out of 7 products, only about 4 reach the development phase, with only 1,5 of these getting launched and only one succeeding. This success rate leads immediately to the question what environment to create to identify as many innovative ideas as possible (Cooper, R.G., 2015). Associated with this discussion are the following topics:

- **Think long term:** in the process to achieve short term targets most of the organisations tend to spend less in R&D and innovative processes.
- **Create an innovative mindset:** the culture of innovative mindset has to be cultivated starting from the top; it must boost creativity by brainstorming new ideas, and thinking “out of the box”.
- **Do not fear to fail:** create a culture of high confidence and allow for some failures.
- **Create an innovation structure and process:** implement a methology framwork and a structured process in evaluating the associated benefits and drawbacks.

- **Understand your customer's needs:** always critical for any innovation is market acceptance by customers.

In consideration of these organisational and economic parameters, the construction process usually has also to manage the following technical requirements and framework conditions as a challenge in an innovation process:

- Restricted construction areas close to some neighbouring buildings which must be integrated.
- Short building phases with partially overlapping process cycles and restricted and limited infrastructure and accessibility of the construction area.
- High requirements for minimum deformations and settlement/subsidence as well as for minimised emissions (noise, dust, smell, visual, vibrations…).
- High requirements for resource-protecting building methods and for health and safety protection.

This combination of economic and technical requests inevitably requires a modification of the current technologies and approaches in the construction process, and promotes demand led innovation to comply.

4 INNOVATIVE SOLUTIONS

With the increasing demand in reuse of inner city areas and the urgent need for deeper foundations in constricted areas, adjacent structures in close proximity, and high ground water levels the well known technologies are often too time consuming and occsasionally not economical to install. The alternatives for these specific cases could be advanced technologies such as jet grouting or deep mixing applications (Kirsch, Sondermann, 2003).

4.1 Modernisation of the Victoria Station in London

The upgrade of Victoria Station in the centre of London, where the Victoria and District & Circle lines cross, involved construction of a new ticket hall on the north side of Victoria Street, an extension and modernization of the existing South ticket hall, the building of eight elevators providing step-free access from street to platform levels, and an underground walkway to the mainline station. Many of these new structures were built at the level of the interface between London clay and water bearing terrace gravels; construction took place next to or beneath the foundation of buildings listed as being "fragile". The crowns of the District & Circle line tunnels are just 2.5 m below street level in some areas, and the crown of the Victoria line is about 14 m below ground. These challenges dictated that the new tunnels, ranging from 4.5 to 9 m in diameter, be constructed at shallow depths, with an axis approximately 10 m below ground surface and clearances of less than 10 to 30 cm from essential LU assets in places.

To enable safe tunneling in the challenging ground and site conditions, about 2,500 interlocking jet grouting (Soilcrete) columns, ranging in diameter from 1.4 to 1.8 m, were installed to depths up to 14 m to provide a watertight annulus around the planned tunnels with a minimum thickness of 2 m. Their placement required continuous refinement and improvement, including the "leap of faith" needed to apply BIM to a complex ground treatment process on an unprecedented scale. Spatial visualization of the planned arrangement of Soilcrete columns along the underground structures of the Victoria Station is shown in Figure 1.

The requirements regarding the design and orientation of these columns, as well as the sequencing of jet grouting works, were driven by a risk review of each individual column, taking into account criteria such as soil type, column installation and proximity to sensitive structures and numerous underground utilities (Fig. 2).

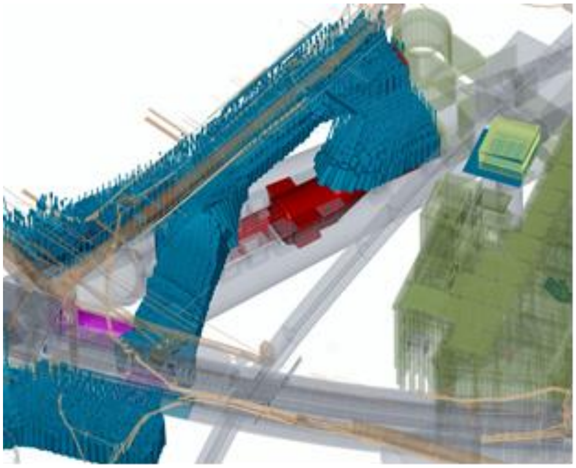

Fig. 1. Visualization of planned jet grouting works at the Victoria Station (initial model prepared by Taylor Woodrow BAM Nuttall JV and the designer Mott MacDonald).

To identify, survey, and model these utilities and to plan the orientation of Soilcrete columns to ensure sufficient coverage and safe tunneling environment, a comprehensive GeoBIM 4D (the fourth dimension was time) model was created and implemented. Figure 3 presents a sample section of the model and shows the alignment of Soilcrete columns adjusted to the location of underground installations and ground conditions. One of the most complex execution tasks was the careful measurement of the orientation of the drill string using GPS sensors at the top and bottom of the masts in order to achieve the required 50 mm tolerance. In addition, column diameter was monitored using the thermal degradation technique. Thanks to accurate as-built data and the enhanced model functionality, the adopted GeoBIM could be also used to analyse the safety of the excavation works under the protective cover of the constructed Soilcrete block.
For this purpose, a preceding simulation of tunnelling works conducted with the NATM method was performed to detect potential gaps inside the Soilcrete block which could pose a risk of groundwater inflow and/or loss of tunnel crest stability. Figure 4 shows an sample simulation made for the pedestrian tunnel, which illustrates the as-built jet grout annulus and the gaps identified in subsequent cross-sections of the tunnel.

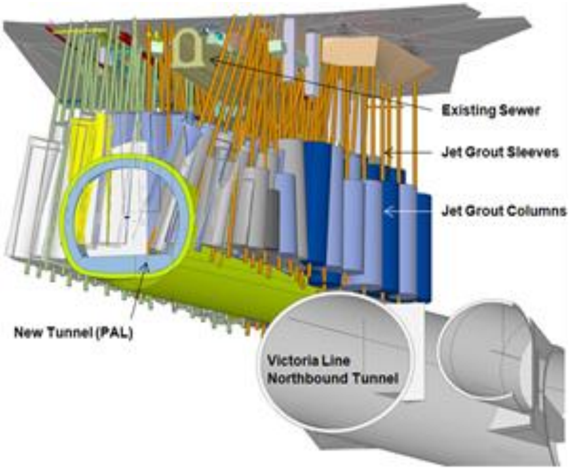

Fig. 2. Arrangement of Soilcrete columns, modelled with the GeoBIM

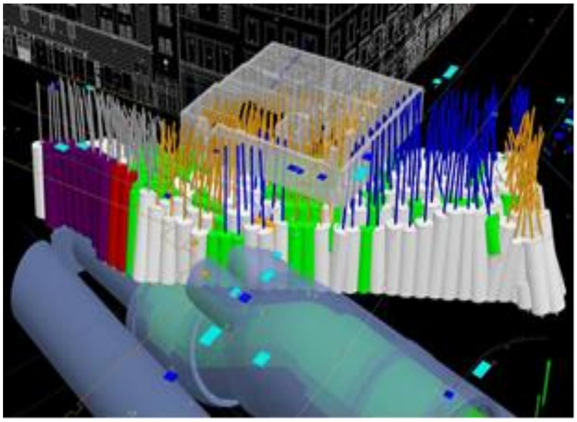

Fig. 3. GeoBIM enables review of Soilcrete columns

The described GeoBIM, which represents part of a more comprehensive BIM used for the entire project, was developed for the needs of a large and complex construction project, and represents a leading example of a mature model comprising a broad scope of information. The full BIM embraced 18 separate design specialties, and enabled direct exchange of information between them. According to the user, London Underground, implementation of BIM into the project allowed them to achieve the following:

- Shorten the time of design works and preparation of more accurate documentation, eliminating errors and collisions to a greater extent.
- Quick implementation of design changes, with a possibility to repeat the calculations, correct measurements and update the executive drawings with a minimum associated workload.
- Improved control of the works' planning and performance, quality and compliance with technical specifications.

Furthermore, it is expected that when all construction tasks are completed, the established BIM, comprising full technical documentation and a virtual model of the whole project, will provide all users with a greater ability to manage station resources**.**

4.2 The Royal Castle Warsaw

The Royal Castle Modernisation Project required the construction of an underground double-floor machine hall under the courtyard of the 18th century palace. The total project assumed a 10m deep excavation below the existing courtyard surface. The design and execution were highly restricted by historic structures in the subsoil, which resulted in a complex layout of the excavation.

The historical Palace is founded at the Vistula river slope, with the upper layer of subsoil consisting of of 2 to 8m thick uncontrolled deposits underlain by fine sands and Pliocene clay. The groundwater level was measured at depths of 2 to 6m below ground surface with the hydraulic gradient linked to the Vistula River running at toe of the slope.

The client's design consisted of conventional secant bored piles wall and tie back anchors; this included many execution risks and disadvantages (such as open borehole stability, required space to adjacent buildings, installation of reinforced cage, discharge material costs, and time for execution). To overcome these challenges in complexity and competitive pressure, a much more environmentally friendly solution involving the use of existing soil as construction material was designed. The advanced technology, in combination with a new design approach (Topolnicki, 2013) as alternative solution, was offered to the client and finally accepted.

Fig. 4. Simulation of tunneling works with the GeoBIM and location of potential gaps inside the Soilcrete block. (a) Forecasted location of main gaps.(b) Exposed tunnel cross-section and leakages

The temporary construction of the excavation pit down to 10m depth (Fig. 5) up to 8m below the existing groundwater level was designed as a structural retaining wall of DSM columns 700mm in diameter and spaced 550mm apart. The wall was constructed with overlapping deep mixing columns to provide water tightness and steel H-beams installed into every second column to create the lateral support system and to provide the required overall wall strength. Soldier piles (every second column), reinforced with steel, were embedded 4.50m below the final excavation level. To achieve the required strength in the mixed columns, the mixing time was elongated with full re-stroking of the mixing tool required to ensure proper conditions for the installation of soldier elements immediately after mixing.

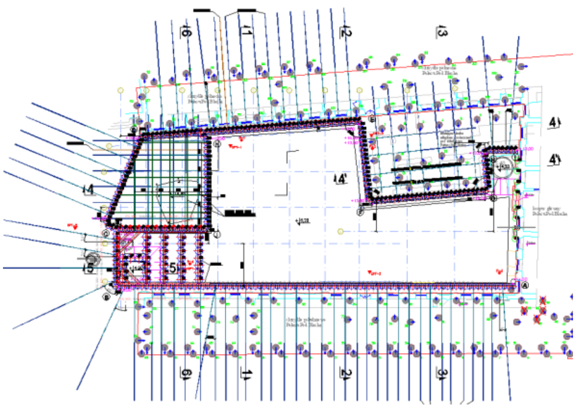

Fig. 5 Excavation layout, lateral support system and tieback anchoring scheme

Fig. 6 Single auger deep soil mixing with pre-stressed soil anchors

During excavation, the wall was anchored with a system of two and three rows of pre-stressed anchors (17 to 18m) in one part of the foundation pit. In order to avoid drilling through the historic structures and monuments, a steel strut system was installed as an alternative (Fig.6).

Due to the complex nature of the total project, the structural analysis was conducted using the finite element method (FEM). A series of variant analyses was conducted using the simple Mohr-Coulomb (M-C) and advance isotropic hardening model (H-S) constitutive models.

To document the quality of execution, an automatic measurement device system was implemented. The measurements proved that the excavation support system succeeded in limiting soil movements and protecting surrounding buildings. Lateral displacement of the palace's wall did not exceed 4mm.

Using this much more economical approach involving a more environmental friendly technology (limited discharge, soil as construction material, limited amount of cement added to the ground), and documenting all the processes and impacts on the adjacent structures, a highly complex project was managed professionally. The project demonstrates that advanced analysis and design options are already available to be used in future challenges.

5 CONCLUSIONS

Innovative solutions in use of new or improved technologies, as well as the changing and adjusting of existing technologies to suit the specific requirements of the project, can contribute to generating an increase in value for the owner. These approaches can also play their part in meeting the future challenges to reduce complexity, to increase quality through automation and documentation, as well as to strengthen the global competitiveness.

To create innovative ideas and implement these products successfully into the market, organisations should consider the following recommendations based on lessons learned from many applications:

- Innovation is less a question of budget but of heads.
- Continuing improvements are more common than breakthrough innovations.

- Innovation is more a question of creativity and quality than a matter of money (good, excellent ideas).

As already mentioned, before the cultural infrastructure for R&D is the most critical part to be innovative and having a high success ratio:

- Clear leadership.
- Clear organisation.
- Clear progress reporting.
- Clear empowerment.
- Clear communication and access to information.

Within the different R&D projects, a clear policy and terms of reference are a key to success as known from project management best practice:

- Clear goal definition.
- Alignment of actions to goals with clear milestones.
- Monitoring of results and costs incl. progress reports.
- Clear responsibilities.

Considering this guidance for geotechnical engineers, the main future challenges require familiarity with theoretical as well as practical applications of advanced technologies to identify for a specific project the optimal combination of technologies, including the best design approach to stay competitive (Sondermann, 2012).

To cope with this more general and conceptual formulation to identify, develop and implement innovations into the organisation, the following summarized capabilities and competancy of geotechnical engineers are required:

- Deep knowledge of technologies and processes including the limits of application of the different technics.
- Excellent judgement on subsoil characteristics and stress strain relationships of soil materials.
- Advanced design capabilities including judgement regarding application of design model and approach.
- Understanding the execution process and the impact of the process on adjacent structures and the environment.
- Fair judgement on technical requirements versus products involved including alternatives.

In addition to technical skills, geotechnical engineers should have knowledge of:

- Planning and organizing.
- Analysing and structuring.
- Accuracy and reliability.
- Team work and relationship with colleagues

to support and advance innovation from the idea to implementation.

Those geotechnical engineers that develop a sound and perfect combination of technical expertise and the soft competences will be fit for future challenges. The goal of geotechnical engineers should be not only technical knowledge, but also shape interpersonal skills.

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