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Tunnels and Underground Spaces:
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The invisible SEM
Flexible tunnelling method in urban areas

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ABSTRACT
Many urban infrastructures are being moved underground as the way to create new green areas on surface and improve the citizens quality of life. Tunnel Boring Machines (TBM) has recently jumped an astonishing step in this field allowing safe excavation in soft ground even below water table. But not only round tunnels are needed to fit operational requirements also caverns, underground stations, bifurcations, cross passages etc. has to be built under congested urban areas at usually low overburden packed with utilities. The now so called sequential excavation method (SEM) has proved to be the most flexible tool to construct complex underground structures adapted to the required geometry and clearance for its final use. Most cities today restrict blasting therefore improved massive roadheaders are taking over providing reasonable production rates combined with low noise and vibration levels. None or minimal utility and traffic relocation is required nor construction of temporary access to buildings or garages. Examples of cities like New York, Seattle, San Francisco and London are provided.

RÉSUMÉ
Nombreuses infrastructures urbaines sont en train d'être mises au souterrain à fin de créer des espaces verts et d'améliorer la qualité de vie des citoyens. Les tunneliers ont donné un grand pas a l'avant dans cette domaine, en permettant des excavations plus secoures en sols même au dessous de la nappe phréatique. Mais pas seulement les tunnels ronds sont nécessaires pour l'opération mais aussi des cavernes, stations de Metro, bifurcations et galeries de connexion faut les construire dans un environnement urbain, généralement avec une couverture réduite et plain de services. La méthode maintenant appelé SEM (Méthode d'excavation séquentielle) a démontré être l'outil plus flexible pour construire des structures souterraines complexes et adaptés en géométrie et gabarit à l'usage final. Dans la plupart des cités l'explosif est interdit et alors des nouveaux et améliorés fraises sont arrives en offrant des raisonnables productions avec réduites niveaux de bruit et vibrations. Aucun ou trés réduite aménagement des services existants est nécessaire, non plus la construction des accès provisoires aux bâtiments et garages. On montre des exemples de cités comme New York, Seattle, San Francisco et Londres.

1 INTRODUCTION

This paper has been prepared in order to call the attention to the tunneling community about the advantages that the so called SEM have in the tunneling construction in urban areas.
The current urban requirements to improve the quality of life of the citizens goes to move underground the existing infrastructures and generate free green areas on the surface. Metro systems, sewage channels, cable networks and others can be easily transferred below the ground and in most of the cases, due to the relevant length of those infrastructures the tunnel boring machines2. have been used for this purpose.
Earth pressure balance TBM (EPB) and hydroshield allows the excavation under pressure in order to compensate the ground deformation and avoid surface settlements, enlarging dramatically the capabilities for tunneling in soft ground. But, not always the ground is so poor and below the water table neither so long the tunnel that pressurized TBMs are the only choice. Additionally operational issues usually require changes in the tunnel shape and size. On the other hand, in the case of sound ground and hard rock, excavation with explosives is restricted in most of the cities due to security and safety concerns.
In these cases in which the limited length of the infrastructure as well as the variable geometry is required, the sequential excavation method has been proved as the most valuable tool to build the underground space cheaper and faster. Depending on ground conditions, hard to soft, excavation can be done by controlled blasting if allowed, drill and split, roadheader or digger.

2. CONSTRUCTION ALTERNATIVES

The two main alternatives to the SEM are the TBM and surface methods as cut and cover or the open cut technology. Both of them should be considered not competitors but construction methods to be applicable in those areas in which they are more attractive in terms of cost and schedule. But, in general, the three of them can be even compatible and applicable in the same project in accordance with the designer criteria and local circumstances.
It is true that surface methods are simple and cheap in those areas without any interference with local utilities

and only in the cases of shallow infrastructure. This is not the case usually in urban environments were the excavation of an underground space requires the relocation of a substantial number of utilities like sewage, water, phone, light, gas, communication, etc. Every one of those utilities is owned by different organization and the removal and relocation could take years especially because many times the contractor cannot manage it from an early stage and so it has no control in the selection of different/other possibilities. That means the project completion is on the third parties hand with not always interest on the completion in time. This fact can be enough to reject the cut and cover as the selected working method in congested urban environment.

Figure1. Cut and cover launching portal Madrid *Calle* 30

Also limits in noise and vibration are every time more and more a contractual requirement and consequently all the activities executed above ground are restricted in time and resources. Adding to these facts the stakeholders' rejection to any construction activity in front of their own business or residences makes the cut and cover a reasonable method to be applied in free areas but not in urban areas.

Even in the case of very poor ground below water table a careful analysis of alternatives between cut and cover and the excavation by SEM with pre excavation grouting should be considered before taking the final decision.

The use of a TBM is a solution for linear tunnels with fix geometry and which is suitable for all kind of ground. The key point is to select properly the TBM in accordance with the knowledge of the existing ground. Very short tunnels that do not deserve the investment in a TBM as well as additional infrastructures required for operational purpose like cross passages, maintenance rooms, etc can be easily constructed by SEM as well.

3 ADVANTAGES OF SEM

The title of this paper is self explanatory. Invisible SEM means no citizens disruption on their own activities, neither disturbance during the tunnel construction. Tunnel portal can be positioned out of the congested area or even out of the contractual alignment in order to minimize this fact. The excavation of additional adits to connect the site portal or shaft with the required infrastructure is an affordable cost compensated by the advantage of no utilities relocation, traffic diversions and others construction disruptions.

The most important requirements/rules of SEM are the following:

• The excavated cross section should always be an ovoid shape.

• Installation of immediate and continuous smooth support around its perimeter (and, if required, smooth support at the face) is a significant factor in minimizing initial movement in the surrounding ground.

• It is also essential to structurally close the supporting ring (shotcrete) as quickly as possible within one tunnel diameter of the advancing excavation face.

The 3-dimensional stress redistribution around the tunnel depends on geometry and time. This must be carefully considered particularly where multiple openings are planned. It will govern the progress of tunneling with respect to stress redistribution interaction and the hardening of the shotcrete support.

After providing the basic design parameters, the required thickness of support (shotcrete) for a given tunnel/shaft diameter and overburden is basically a reversed function of the internal angle of friction of the formation. Calculated bending moments in ovoid shaped tunnels have little to do with reality. Heavy reinforcement in the lining only weakens the shotcrete support capacity due to shadowing and, therefore, produces an inconsistent lining with a questionable shotcrete quality. Proper structural models applied with skill and experience result in minimum bending moments and therefore require less reinforcement.

Continuous (and, if applicable symmetric) excavation of (multiple) drifts avoids heterogeneities in stiffness and smoothes the stress redistribution in both the lining and the surrounding ground.

Figure 2. Tunnel excavation with ripper

In relation with the construction itself, SEM has multiple advantages. The excavation can be accommodating to the required geometry for operational reasons and in accordance with ground conditions, excavation stages and support can be easily adjusted. The well known toolbox is the key of success of this method and any kind of ground condition can be handled safely by following the incremental excavation / support or

pre-support approach together with observational measures to be implemented during the excavation.
Geometry and Progress may vary from full face to subdivision of the excavation face in top heading, bench, side wall drift, or multiple drifts, etc. The reduction of the length of round or, if necessary, continuing excavation and support flow around the clock in extremely soft ground, influences the progress. Geometry and progress can be adapted as necessary.
Pre-support may start with dewatering of the excavation area and/or spiling with various elements. The barrel vault method is probably today's most effective pre-support over longer stretches. Horizontal jet grouting also improves the ground ahead of the excavation line as does conventional grouting of the surrounding ground.
Face support may consist of only the existing ground (earth wedge) or additional shotcrete, or even face bolting. Pocket excavation or multiple drifts are another safe and effective face support technique.
Special methods (i.e. Ground freezing, Barrel Vault Method or Doorframe Slab Method etc.) provide a variety and enormous number of possible combinations to tackle any kind of ground. It allows mining in all ground conditions and through all obstructions, including buried foundations without compromising geometrical requirements. This is also true for excavation of large caverns with minimal cover.
In urban areas surface deformation (settlements) causes more and more environmental problems. It cannot be avoided but can be minimized and/or compensated by grout injection adjacent to the underground structure. This compensation grouting has successfully been applied in a number of cities worldwide, London, Barcelona, Toronto, etc.

4 CRITICISM AND MISCONCEPTIONS ABOUT THE METHOD

In tunneling conferences and publications is not uncommon to hear concerns about the safety of SEM mostly in urban tunnels. SEM must be regarded as a 3D concept to understand its way to control and distribute the ground loads on these complex shapes that are the underground structures.
The success of execution of the SEM is based on four premises:
• Thoughtful design by an experienced engineering team
• Execution by a skilled contractor
• Competent supervision
• Interpretation of monitoring results
SEM is an observational method (R. Peck), which means that monitoring (in-situ-measurements) of deformation in the ground and stress in the initial lining (shotcrete) is essential to the actual support means.
A weak design or poor performing contractor can be improved always by proper supervision and interpretation, avoiding collapses and damages to third parties.
The graphic shows a substantial amount of tunnels built by SEM with low overburden successfully.

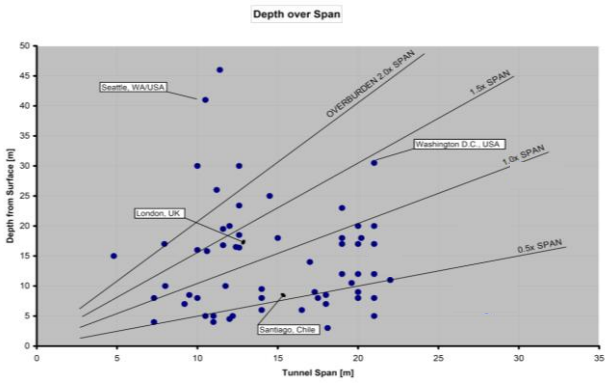

Figure 3. Tunnel span vs. Overburden

Even seismic activities do not pose a serious risk to completed tunnels. The physical principle behind this is simple: The sequential excavation produces a stress relieved (relaxed) zone around the tunnel while immediate sprayed smooth shotcrete support forms a composite structure with the surrounding ground.
This cushion effect and its shell structure provide flexible resistance against shock and shear waves (Friaul, Northern Italy, 1974).
In contrast, cut-and-cover structures are prone to adverse stress peaks impacts, which can lead to their total destruction (Kobe, Japan 1995).

5 RECOMMENDED EXCAVATION EQUIPMENT

In sound ground without urban restrictions, drill and blast seems to be the most economical way to build tunnels and can be adapted to the variable geometry of the structure. Control blasting can be a tool to deal with urban restrictions. But not always the ground is so grateful neither explosives are allowed to build the tunnels and consequently different excavation methods and equipment must be chosen.
In the same way that TBMs have experienced a huge development in the last decades, conventional equipment is more and more powerful and capable to deal with a large range of ground conditions. Based in previous experiences, the attached table shows the limits of the state of the art in tunneling equipment to our knowledge.
The distribution is related to the rock compress strength and the R.Q.D. assuming that lower R.Q.D. allows excavating with the same equipment at higher compress strength of the rock.
It is remarkable on the table the high performance achieved by roadheaders, being able to deal with rocks up to 150 MPa and 100% R.Q.D. despite achieving low production rates.

Figure 4. Roadheader MT-720 at East Side Access (New York)

Also hammers are currently heavier and powerful but the limitation in their application in tunneling is related to the associated carrier. That's mean; a strong 4000kg breaker requires a 40 to 70 ton backhoe, big enough to make not viable their use in most of the tunnels.

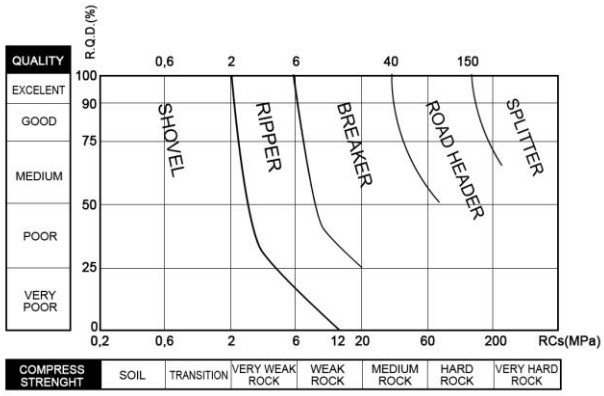

Figure 5. Recommended excavation equipment

On the highest strength of the rock were roadheaders are not able to excavate with reasonable rates, the alternative is the splitter. Drill and split is a solution in those cases were explosive is not allowed and there is not any other equipment able to deal with the hard rock. Also the production rates use to be quite low, mainly due to the astonish amount of holes to be drilled at the face in order to be able to brake the block by hydraulic wedges. Additionally a free face is required in this method to initiate the excavation. This starting face can be done by secant holes or with diamond disc cutter.

Figure 6. Drill and split excavation

6 CITIES JOINING SEM

In Santiago, Chile, 150m² station caverns were excavated 7-9m below the city streets for the Metro. The cavern's face is divided into side-wall drifts and a central core section.

Figure 7. Station cavern Metro of Santiago (Chile)

Each section utilizes a top heading, bench and invert sequence. This approach eliminates the need for forepoling or spiling ahead at full span top heading rounds under shallow cover and allows optimum rotation of medium size equipment and crews between several advancing faces.

Figure 8. Grand Central Station cavern (New York)

The East Side Access Project is part of the connection of the Long Island Rail Road to the Grand Central Terminal in Manhattan NY. Two TBMs, from SELI and Robbins were assigned to built the running tunnels but substantial amount of cubic meters of excavation in this project are related to areas with variable and not rounded geometry, bifurcations, cross passages, operation rooms and the two main caverns 344 x 20 x 18 m each. For it excavation a combined process of TBMs, roadheader and drill and blast has being applied.
Rock bolting plus shotcrete layers have being the temporary support installed.

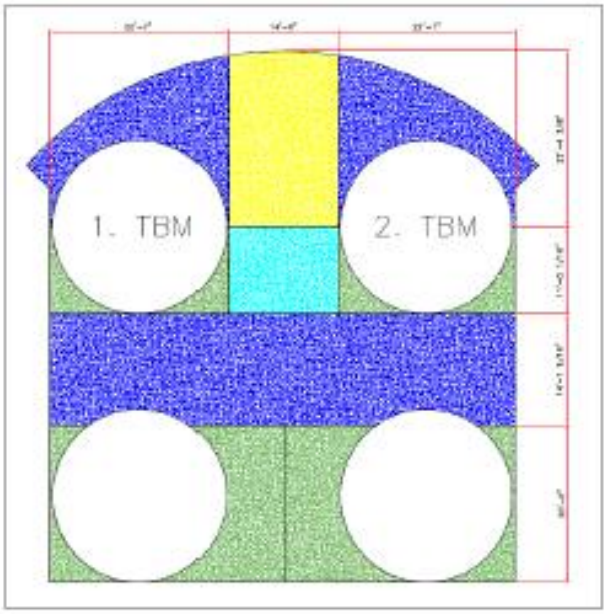

Figure 9. Grand Central Station excavation stages

Seattle, the city which deserve the privilege to allocate the world largest TBM tunnel for the Alaskan way replacement project, has also experience in SEM.

Figure 10. Beacon Hill Station

Beacon Hill is a Light Rail Station located 46 m beneath surface. Station complex includes central elevator/access shaft, concourse, opposing platform tunnels and cross passages. Predominant geology is Soft Ground, over-consolidated glacial clay and till with fractured zones together with intermittent sand and silt layers with perched groundwater.

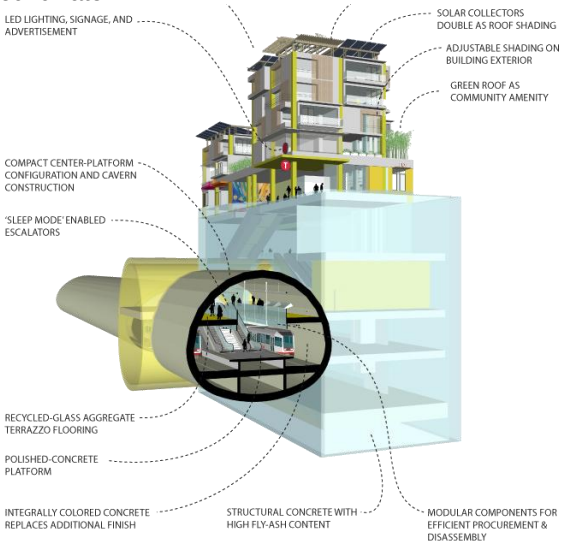

Figure 11. Chinatown Station San Francisco

The San Francisco Municipal Transportation Agency (MUNI) is building a 1.7 mile underground extension to the Third Street Light Rail Project.
The underground section start near Bryant Street, run along Third Street, cross under four BART Tunnels at Market Street and continue under Geary and Stockton Streets to Clay Street. Underground subway stations are located at Moscone Center, Market Street, Union Square and Clay Street in Chinatown.
The geology ranges from soft clay (Bay Clay) to stiff sands (Colma Sands) and competent to highly fractured rock (Franciscan Formation). A considerable part of the tunnel alignment is below the groundwater table. The

restrictions on surface have recommended the Chinatown Station to be designed and built by SEM.

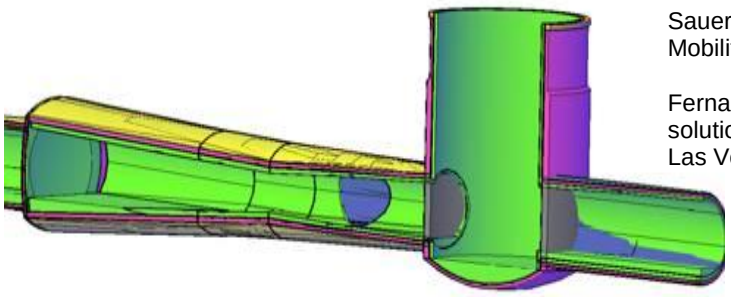

Figure 12. Stepney Green shaft preliminary design. Crossrail

London Underground has a large experience in SEM. The famous London clay is a great ground, easy to be excavated and very adequate to design SEM structures. Latest stations extensions recently awarded or under bid stage are focused in this method. Also the Crossrail Project, linking the East and West suburbs with London core, currently under construction, has envisaged a substantial amount of underground structures to be designed and constructed using the sequential excavation method (Called SCL-Sprayed Concrete Lining)

7 CONCLUSIONS

Every tunnel and underground structure can be built by different methods, all of them with their own pros and cons. During the design stage those cons must be very carefully evaluated in order to overpass them by selecting alternatives.

The Sequential Excavation Method has most of these advantages and very few cons in the case of urban tunnels. It is flexible, easily adapted to the required geometry and to the ground quality, giving the possibility to apply different support or excavation stages to minimize the disturbance in the surrounding ground and in the surface.

SEM gives an additional advantage: the control of the process is in our own hands, with our toolbox and proper knowledge of the ground. It allows the excavation by multiple front faces if required to fulfill the contractual schedule.

The initial investment in equipment is much less than in the TBM process and also the required support use to be cheaper than the precast concrete segments installed as final lining.

SEM also minimizes the impact in the citizen daily activities by opposite to the cut and cover approach.

Collapses in tunnels happen with all the excavation procedures and always are directly related to poor performance in design, construction or supervision. Professionalism and experience is the key to succeed in the construction of underground structures in urban environment.

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