Geotechnical Aspects of Underground Construction in Soft Ground – Viggiani (ed)
© 2012 Taylor & Francis Group, London, ISBN 978-0-415-68367-8

Urban tunnels in soft ground: Review of current design practice

Vinicius da Mota Wedekin
Bureau de Projetos e Consultoria Ltda, Sao Paulo, Brazil

Richard Kastner
Université de Lyon, INSA Lyon, LGCIE, France

Alain Guilloux
Terrasol, Paris, France

Adam Bezuijen
Delft Geotechnics, Delft, The Netherlands

Jamie Standing
Imperial College, London, UK

Arsenio Negro Jr.
Bureau de Projetos e Consultoria Ltda, Sao Paulo, Brazil

ABSTRACT: Current design practice for urban tunnel construction in soft ground as perceived worldwide is reviewed and discussed. The review is based on answers to a questionnaire prepared and sent out by a TC204 working group in 2010 to practitioners involved in the design or in the design supervision of tunnelling projects. The results of this investigation are carefully considered to identify trends and needs for development.

Keywords: urban tunnels, soils, design practice, survey.

1 INTRODUCTION

The first assessment of the design practice involving urban tunnels driven in soft ground (i.e. not rock) was carried out in 1993 through a survey performed in Brazil. The results from this were published in the 1st International Symposium on Underground Construction in Soft Ground in New Delhi by the former TC28 now TC204 (Negro and Leite, 1995).

In 2006 another Brazilian assessment was made, but this time cut-and-cover structures were not included and the review covered underground openings of any shape with more than 0.5 m diameter; directional drilling was not included. The survey was not limited to tunnels built in Brazil but covered any tunnel project conducted with criteria and procedures presently adopted in Brazil. Results from the second assessment were published in the TC28 Shanghai International Symposium (Negro, 2008). TC204 then created a working group to adapt this survey format to review the world design practice.

The present survey focuses on underground openings of any shape with more than 0.5 m diameter and covers tunnel projects conducted all around the world. In all cases tunnels were designed and built in areas with overlying surface buildings and subsurface utilities, both liable to damage induced by ground movements associated with tunnel excavation.

Multiple choice questions to which one or more answers could be selected were sent to professionals involved in the design or in the design supervision of tunnel projects over the past few years. Considering the multi-disciplinary nature of tunnel design, the questionnaire, with 46 questions, was sent to practitioners with a variety of expertise and included topics beyond a strict geotechnical context. Accordingly, questions were sent to geotechnical engineers, geologists, structural engineers and experts in numerical modelling.

These professionals could opt not to answer questions outside their fields of specialisation. In 51% of the cases the respondents were consultants working on tunnelling projects and 15% referred to contractors (Figure 1). Note that TBM suppliers were not involved in this assessment.

Most questions asked for answers that would express the practitioners' current preference on each technical aspect of tunnel design, in such a way that they would reflect the respondents' routine design practice. The questionnaire was answered by 47 specialists in tunnel design from 15 different countries.

Figure 2 shows the distribution of respondents from around the world, revealing a significant concentration in Europe (41%) and an absence of the professionals from North America and Africa.

The results that follow are grouped according to related topics in a sequence that is not necessarily related to that of the questionnaire. One should note that respondents sometimes offered more than one answer to a question. Therefore, frequencies shown refer to the percentage of total answers offered or to the percentage of respondents as appropriate.

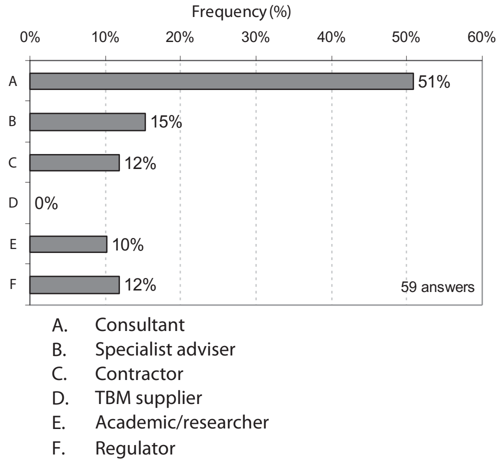


Figure 1. Types of companies/professionals involved.

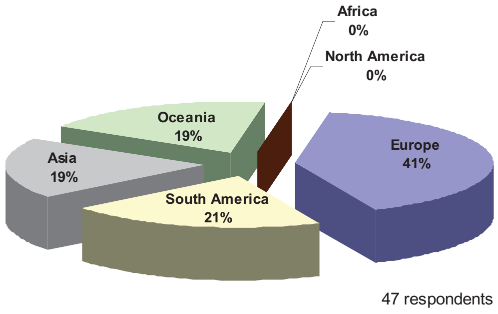


Figure 2. Frequency distribution of respondents from around the world.

2 TUNNEL TYPES AND SCENARIOS

To make the analysis of the answers simpler, a few questions were formulated to define the scenario of the design practice being referred to.

More than three quarters of the answers refer to tunnels built for trains, metro systems and vehicles in general (Figure 3).

Accordingly, more than four fifths of the answers (from 37 given) refer to tunnels of more than 6 to 10 m diameter (almost half with diameters in excess of 10 m—see Figure 4).

The ground conditions most frequently encountered were either mixed conditions at the face or hard soil/soft rock tunnelling (Figure 5). Tunnelling through granular (cohesionless) ground seems to be the least common. In most situations tunnelling takes place below the water table (Figure 6).

3 GEOTECHNICAL DESIGN AND CONSTRUCTION

3.1 *Tunnelling general*

Figure 7 indicates that conventional tunnelling with a sprayed concrete primary lining is the most frequently specified construction process. The responses are consistent with the large cross-section tunnels involved, since smaller tunnels are almost always built by mechanized shields.

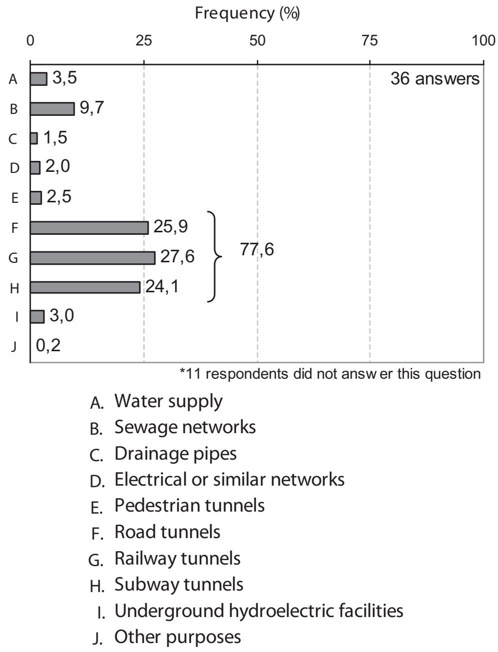
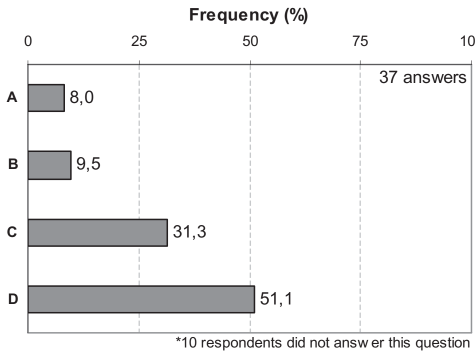
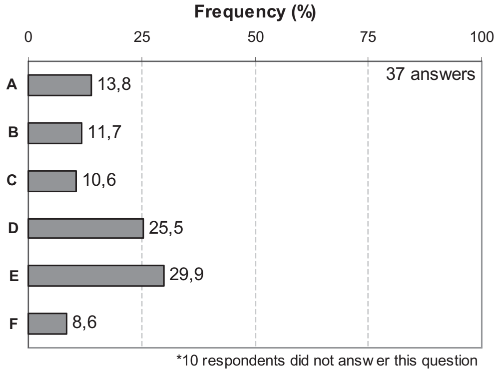


Figure 3. Purpose of tunnels designed.



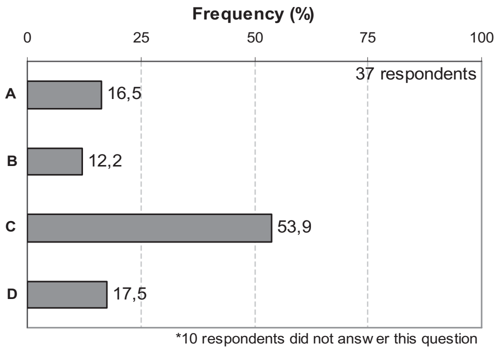
A. between 1.5 and 3.0 m
B. between 3.0 and 6.0 m
C. between 6.0 and 10.0 m
D. greater than 10.0 m

Figure 4. Equivalent diameters of tunnels designed.



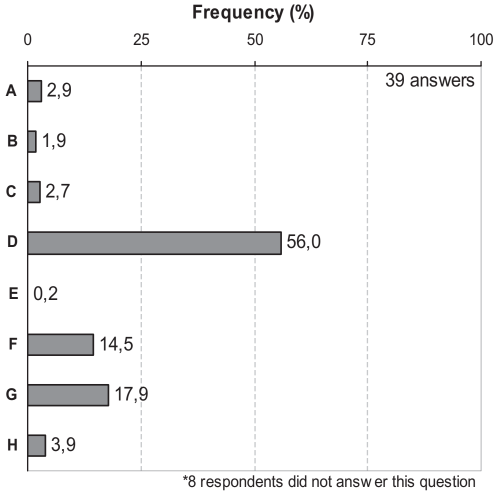
A. cohesive soil
B. soils with small cohesion
C. soils without cohesion (i.e. granular)
D. mixed conditions on the face of the tunnel
E. hard soils/soft rocks
F. other types

Figure 5. Excavated ground mass.



A. below the tunnel
B. in the section of tunnel
C. above the tunnel
D. all previous positions

Figure 6. Water table position related to the tunnel.

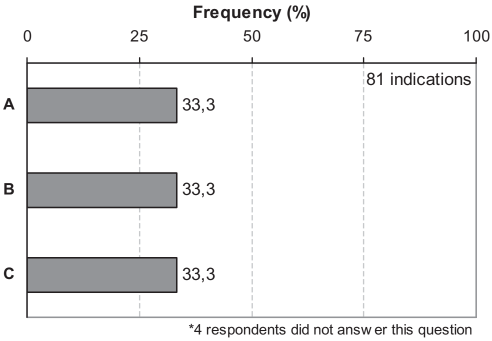


A. pipe-jacking with concrete pipes
B. mini-tunnel system using a shield and
C. tunnel liner with bolted steel segments
D. sequentially excavated tunnels with sprayed concrete lining
E. compressed air shield with segmented bolted rings
F. slurry shield with segmented bolted rings
G. earth pressure balanced shield with segmented bolted rings
H. others

Figure 7. Construction processes used.

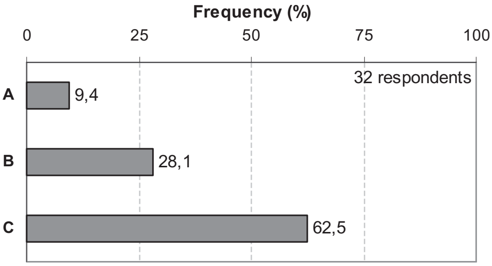
When asked whether they usually specify the construction sequence for conventional tunnelling with sprayed concrete, 28.9% of respondents replied that they do not design or do not specify such a type of tunnel construction procedure whereas the others respondents answered that they do. Those who answered affirmatively stated which construction procedures they specify out of the three listed: a) partial excavation of the tunnel heading face, b) ground conditioning of the tunnel face and c) maximum distance of the primary lining invert closure from the tunnel face. Figure 8 shows that the responses indicated no preference for any of the three procedures listed, which all received exactly the same number of indications.

Figure 9 shows that the majority of the respondents specify all procedures listed. It appears that



A. I specify the partial excavation of the tunnel heading face
B. I specify the ground conditioning of the tunnel face
C. I specify the maximum distance of the primary lining invert closure from tunnel face

Figure 8. Construction procedures specified for conventional tunnelling.



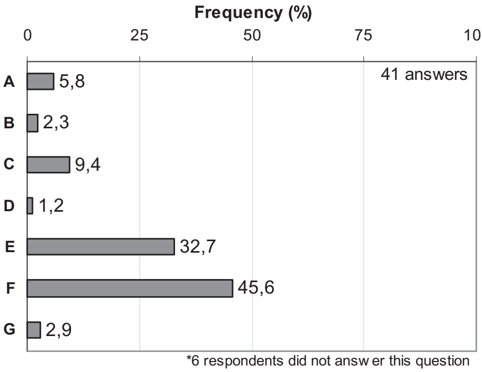
A. I specify only one procedure
B. I specify two procedures
C. I specify all three procedures

Figure 9. Number of construction procedures specified in conventional tunnelling.

there is a general concern to minimize instabilities during excavation as well as damage associated with tunnelling-induced settlements, by specifying stringent construction procedures.

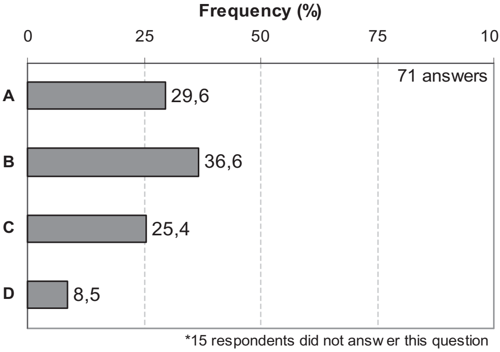
3.2 *TBM Tunnelling*

When referring to mechanized driven tunnels with a shield, the most frequently used type of equipment is the earth pressure balance shield (46%°), while slurry shields are used in 33% of cases, and other types of tunnel boring machine (open face, compressed air or mixed TBMs) appear marginally, as indicated in Figure 10.



A. I do not design shield-driven tunnels
B. I do not specify shield-driven tunnels
C. open face shield
D. air pressure shield
E. slurry shield
F. earth pressure balanced shield
G. other types

Figure 10. Types of TBM chosen for shield driven tunnels.



A. I specify the type and process of the lining back filling (tail skin grouting)
B. I specify the pressure on the face
C. I specify of the maximum ground over-cutting
D. others

Figure 11. Specifications for the operation of the machine for shield driven tunnels.

Likewise for the question on conventional tunnelling, for the TBM operations three construction procedures which have a strong influence on settlements were offered for selection by respondents: specifications for a) lining grout, b) tunnel face pressure and c) maximum overcutting at the cutting wheel. As indicated in Figure 11, face pressure control is the most frequent specification made.

In urban areas, one of the main concerns is to avoid over-excavation and sinkholes.

For this problem (Figure 12), the TBM control parameter which is most often monitored is the face pressure (48% of the answers). Next comes

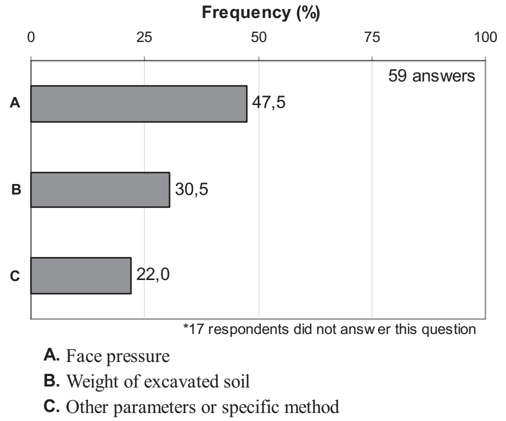


Figure 12. Shield driven tunnel parameters for TBM operation control.

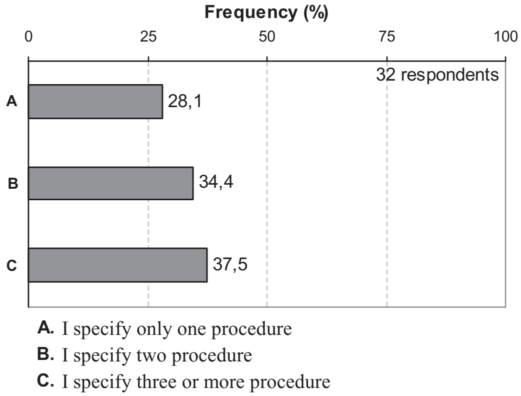


Figure 13. Number of construction procedures specified in TBM operation.

the weight of excavated ground which is monitored in 30% of cases. Additional observations are also often taken into account (22%). Among these additional observations are: the density of the mud, the volume of the excavated ground measured by combining weighing on the conveyor belt and a volume measurement by laser, the injection pressure of the annular void at the shield tail, and the volume of grout injected, followed by other machine parameters such as thrust combined with the torque on the cutting wheel and the use of various methods of field monitoring (e.g. extensometers, radial penetrometers installed in the machine).

Figure 13 shows that only slightly more than a third of the respondents specify three (or more) construction procedures, as opposed to almost two thirds, in conventional tunnelling. In the latter, only 9.4% of respondents specify just one procedure whereas in TBM construction 28.1% specify only one procedure. This may indicate that a more relaxed attitude prevails in the design of TBM driven tunnels compared with conventional tunnelling design.

3.3 *Conventional tunnelling*

Investigating further the importance of construction procedures to be specified in the design, Figure 14 shows the reasons for requiring the closure of the primary lining invert at a certain distance behind the face of conventional tunnels. The majority of the answers indicate stability issues as the main reason, especially in less competent ground, followed second by control of settlements.

When asked how the tunnel designer can act to control the face stability of a conventionally mined tunnel with sprayed concrete as primary lining, the experts (see Figure 15) revealed that their most preferred control measure is face nailing (73% of the cases). Other methods such as forepoling, partial excavation and reduced distance of closure of the invert are also commonly used. The least preferred measure is forepoling using steel piles driven into the ground; a technique popular in the 1970s.

3.4 *Groundwater control*

Figure 16 presents the preferences of distinct measures for groundwater control in conventional and TBM tunnelling. Clearly, with the former, preference is given to de-watering from inside the tunnel and with the latter the use of earth pressure balance systems.

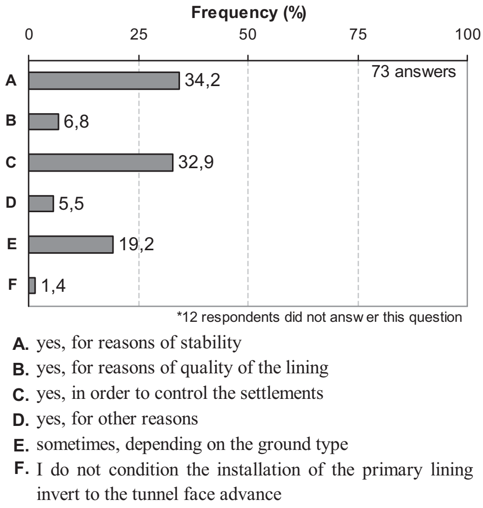
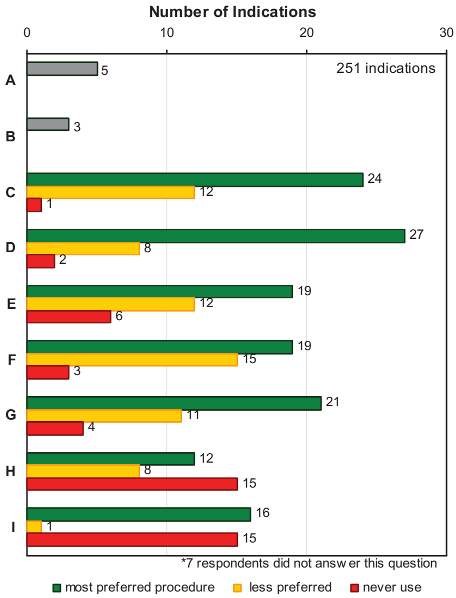
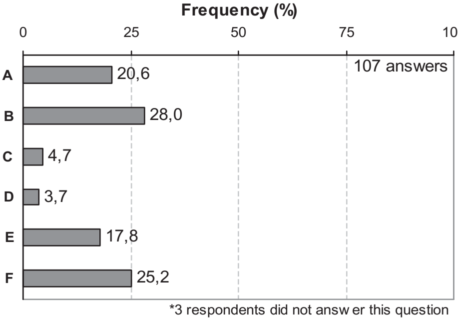


Figure 14. Reasons for closure of primary lining invert at a certain distance behind the face.



A. I do not design sequentially excavated tunnels
B. I do not design mined tunnels that require control of the stability of the face
C. cement injected tubular forepoling
D. face nailing
E. reduction of the distance of invert closure to the tunnel face
F. forepoling and / or face nailing with jet grouting
G. partial excavation of the face (use of side drifts, of temporary invert, etc)
H. steel piles driven (forepoling)
I. other methods

Figure 15. Preferences on measures for face stability control in conventional tunnelling with sprayed concrete primary lining.



A. dewatering from the ground surface (with wells)
B. dewatering from in-side the tunnel
C. dewatering from drainage tunnel
D. closed face system: Compressed Air
E. closed face system: Slurry shield
F. closed face system: EPBS

Figure 16. Groundwater control measures.

4 LINING DESIGN AND WATER PROOFING

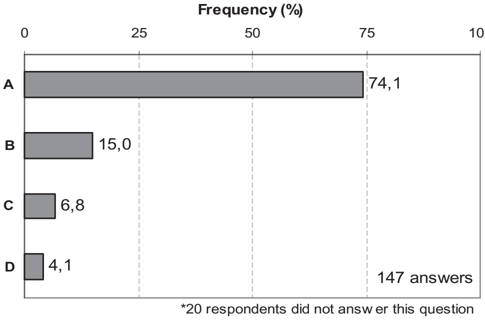
In TBM driven tunnels, the type of lining most frequently used is bolted concrete segments (74% of the answers), as shown in Figure 17. Other types are divided between non-bolted concrete segments (15%), ductile iron segments (7%) and 4% other types of linings, such as concrete pipes installed by jacking, or a concrete cast-in-place lining. From these answers, it is not possible to establish a correlation between the tunnel diameter and the lining type.

For primary linings in TBM construction or conventional tunnelling with sprayed concrete primary lining, wet-mix is most frequently used (83% of the respondents indicated it, see Figure 18) and the least used is the cast-in-place concrete (never used by almost 49% of the respondents, Figure 18).

On the other hand, the most commonly used secondary lining (see Figure 19) is cast in-place concrete, with 78% of the respondents opting for this. Moreover, 68% of the respondents indicated that dry-mix sprayed concrete and steel lining are never used. The responses are consistent with the large cross-section tunnels built in practice. Abandoning steel as a secondary lining material is likely to be connected to its susceptibility to chemical and electrical corrosion frequently present in urban environments. In some parts of the world it might also be because of cost.

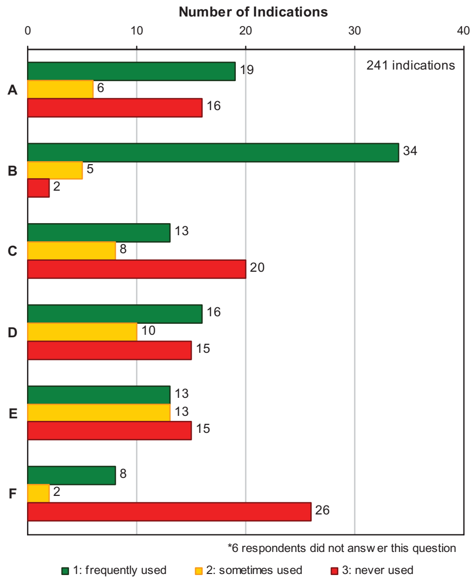
Figure 20 shows that steel bars and welded steel meshes are the most common type of reinforcement used in concrete secondary linings. It is worth noting that synthetic fibres and steel sets are rarely used.

The majority of respondents (78%) require minimum reinforcement in the secondary lining.



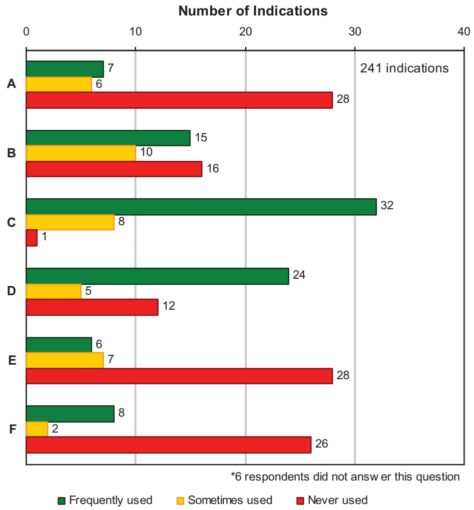
A. bolted concrete segments
B. wedge-block concrete segments
C. bolted SGI (spherical graphite iron) segments
D. other

Figure 17. Secondary lining types used for TBM driven tunnels.



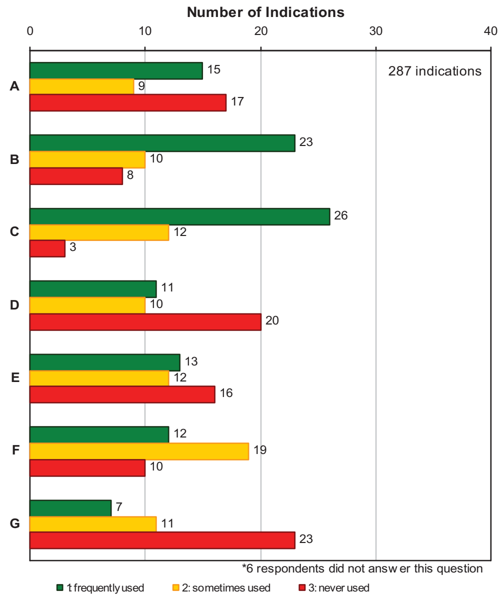
A. dry-mix sprayed concrete
B. wet-mix sprayed concrete
C. cast-in-place concrete
D. pre-cast concrete (segmental or not)
E. steel
F. others

Figure 18. Primary linings for tunnels.



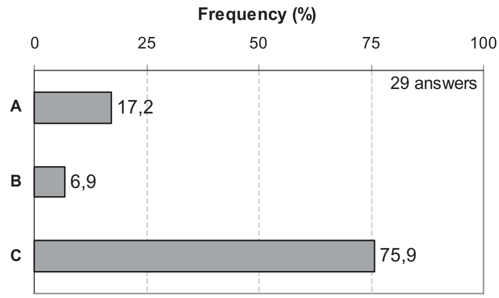
A. dry-mix sprayed concrete
B. wet-mix sprayed concrete
C. cast-in-place concrete
D. pre-cast concrete (segmental or not)
E. steel
F. others

Figure 19. Secondary lining for tunnels.



A. unreinforced
B. welded steel meshes
C. steel bars
D. steel sets
E. lattice girders
F. steel fibres
G. synthetic fibres

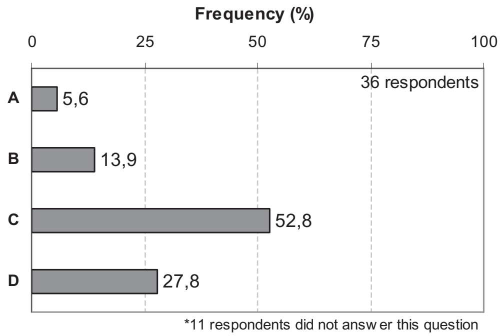
Figure 20. Concrete reinforcement types in secondary lining.



A. Minimum reinforcement for bending
B. Minimum reinforcement for shrinkage
C. both of them

Figure 21. Type of minimum reinforcement adopted.

Only a minority accept reinforcement less than the minimum. When asked what kind of minimum reinforcement is required (Figure 21), 17.2% of the respondents indicated that they adopt the minimum reinforcement for bending only and the majority (75.9%) consider the minimum reinforcement both for bending and shrinkage.



A. never
B. rarely
C. several times
D. ever

Figure 22. Lining designed to be waterproof or watertight.

When asked about the frequency of linings designed to be waterproof or watertight (Figure 22), 19.5% of the respondents declared that they either never or rarely design tunnels for those conditions. The majority of the respondents indicated that they have done it several times (52.8%) or always do it (27.8%).

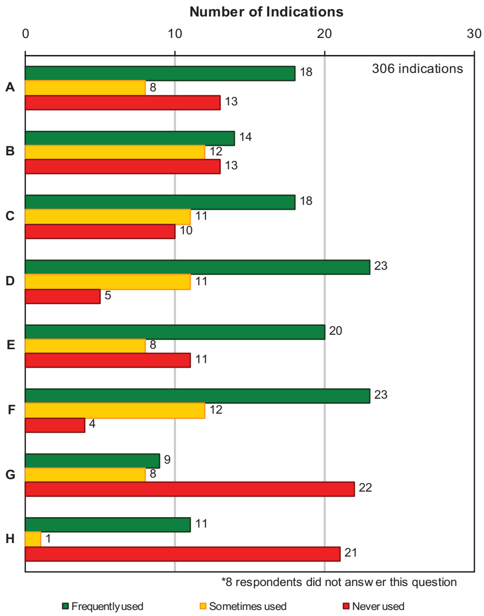
The most frequent waterproofing measures for groundwater infiltration control (Figure 23) are the use of impervious membranes and of limiting the concrete cracking, with indications from 59% of respondents for each. It can be also seen that sprayed membranes are not used much for this purpose.

5 DESIGN PROCEDURES

5.1 *Stability analyses*

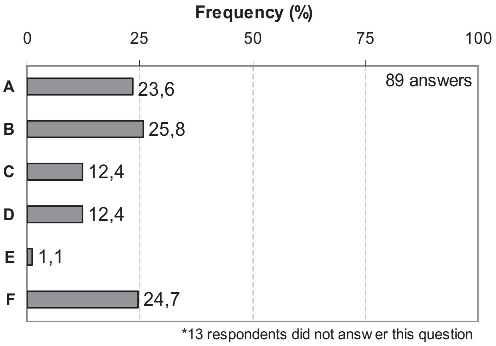
The great majority of respondents (97%) perform stability analyses of the tunnel heading excavation. As shown in Figure 24, limit equilibrium methods are used the most for tunnel excavation stability analyses (25.8%) despite being inaccurate. These are followed by stress-strain analyses and by empirical methods. More rigorous approach of limit analyses by the lower bound and upper bound theorems of plasticity are not used much.

A new class of solutions of tunnel stability analyses by numerical limit analyses (NLA) that combines finite element numerical methods with optimization procedures to find the maximum magnitude of a stress field to cause the collapse of the ground around the tunnel heading face without violating the failure criteria does not seem to be used much yet in practice.



A. special concrete mix
B. use of special additives in the concrete
C. controlled curing of the concrete
D. limiting the cracking of the concrete
E. use of rubber seals
F. use of impervious membrane
G. use of sprayed membranes
H. others

Figure 23. Groundwater infiltration measures adopted.



A. empirical methods
B. limit equilibrium methods
C. limit analyses, Lower Bound Limit Theorem.
D. limit analyses, Upper Bound Limit Theorem.
E. numerical limit analyses (NLA)
F. stress-strain analysis (analytical or numerical)

Figure 24. Methods for stability analyses of tunnel headings.

The final questions of the part related to TBMs concern the specification of the confining pressure at the face.

According to Figure 25, two thirds of respondents use distinct procedures for stability analyses of headings of conventional and of TBM driven tunnels.

Those that use different approaches were asked how the pressure to be applied at the tunnel face is to be defined. They showed a preference for limit equilibrium solutions (Figure 26), despite their theoretical limitations. It should be noted that, in most cases, several approaches are used. Thus, a detailed examination of responses shows that the empirical approach is never used alone. Similarly, with one exception, the numerical stress-strain analysis is always used in conjunction with other methods. Generally the simplified approaches might be considered as inadequate as they are not accurate for assessing the stability of the face and are used only as a first estimate. Usually they are supplemented at a later stage by more rigorous approaches.

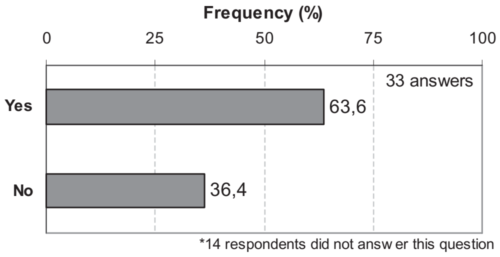


Figure 25. Use of distinct approaches for stability analyses of tunnel heading in conventional and TBM driven tunnels.

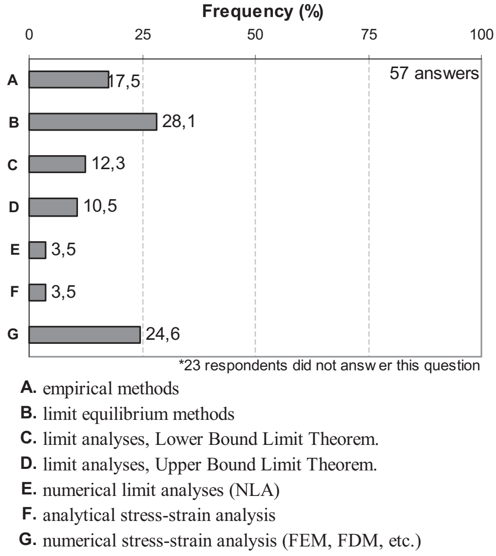


Figure 26. Approaches used to define the pressure to be applied at the tunnel face.

5.2 *Settlements and their influence on surroundings*

Almost all respondents (97.8%) routinely perform predictions of settlement associated with tunnel excavation. More than 50% of the answers indicated numerical methods (finite element or finite difference) as the usual tools for such predictions (Figure 27). It should be noted that empirical and semi-empirical methods are also still in use for this purpose, summing 45% of the answers.

For the assessment of potential damage to surface structures by tunnelling-induced soil displacements, preference is given to the method by Mair, Taylor and Burland (1996) in 34.3% of the answers (Figure 28).

It was noted (Figure 29) that the majority of respondents (74%) always perform preliminary studies to evaluate the sensitivity of existing buildings and structures to tunnelling-induced damage.

When using finite element or finite difference approaches, a key aspect is the choice of the soil model: in the survey various types of model were considered and can be grouped into two main categories.

- Category A: includes two models that at very small strain ranges display linear responses; they are the linear elastic model and the elastic linear-plastic model associated with the Mohr-Coulomb failure criterion.
- Category B: includes models that at small strain ranges display non-linear responses; they are nonlinear models able to represent more accurately the actual behaviour of most soils.

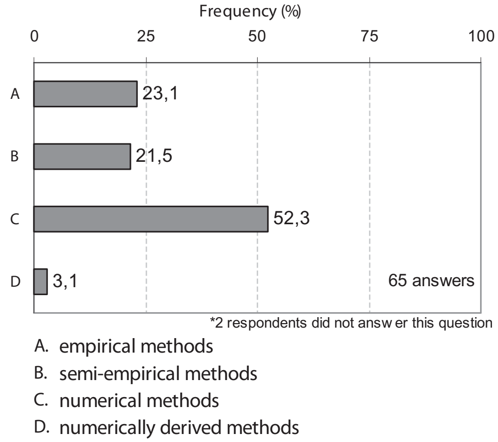


Figure 27. Methods used for estimating settlements.

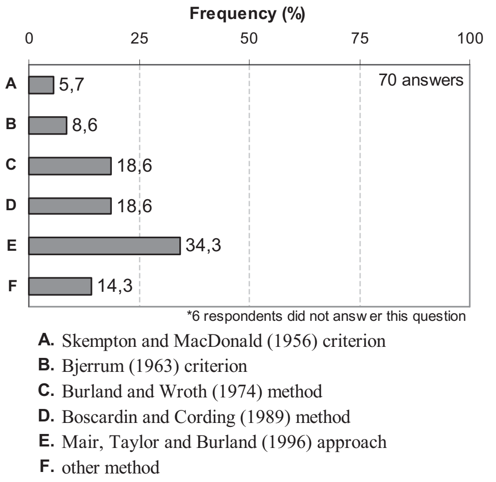


Figure 28. Methods for assessment of potential damage induced in surface structures by tunnelling-induced soil displacements.

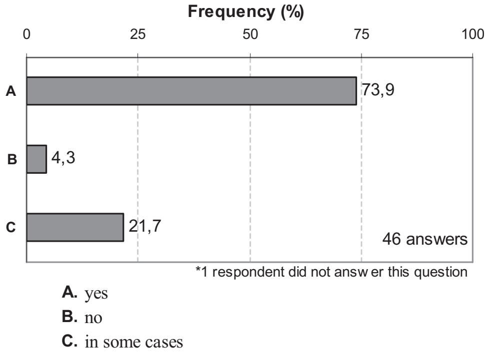


Figure 29. Preliminary assessment of the sensitivity of existing buildings to settlement damage induced by tunnelling in urban areas.

Figure 30 shows that two thirds of the answers refer to models of category A, which do not represent accurately the behaviour of actual soils. Only one third of the answers indicate that these respondents use non-linear models. This may reflect that practitioners are better acquainted with category A models, being part of a standard knowledge to many and, more importantly, available in most commercial computer codes, particularly because of its numerical simplicity and hence ease of use. Models within category B were developed later, are not always available in commercial codes and tend to be more cumbersome in handling both numerically and practically, although they portray better the real soil response.

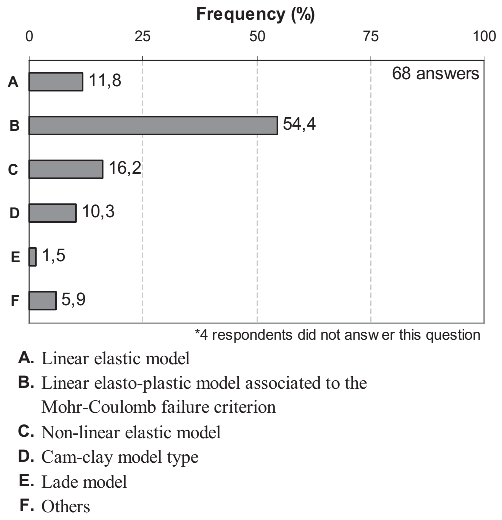


Figure 30. Constitutive model of soil behaviour adopted in numerical analysis for tunnelling projects.

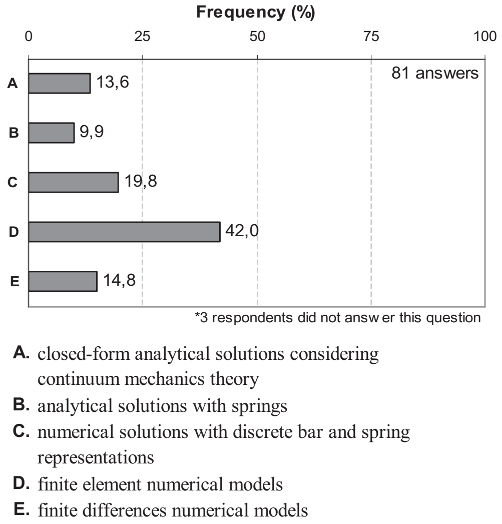


Figure 31. Plane-strain solutions for the interaction between lining and soil.

5.3 *2-D Lining and soil interaction*

For the assessment of the interaction between lining and soil, in plane-strain conditions, a variety of solutions was offered to the practitioners as indicated in Figure 31.

By and large, numerical solutions by finite elements or differences are the most quoted solutions adopted in practice. However, the oldest simplified approaches largely coexist with the finite element or finite difference method approaches. This coexistence is reflected by the fact that there are many multiple responses (50% of the respondents use two methods or more).

It has been noted that when calculating the primary lining using plane-strain solutions, two thirds of the practitioners assume a reduced overburden (see Figure 32). Methods most frequently used for estimating the reduction in the ground overburden are numerical or numerically derived (for instance, Negro and Eisenstein, 1997). These are followed in popularity by Terzaghi's arching theory (see Figure 33), despite the fact that this method implies a considerable ground stress reduction which is associated with large ground deformations and settlements, a situation to be avoided in an urban environment, besides being unsafe.

When analysing the secondary lining (see Figure 34) the reduced overburden assumption still prevails but less than noted for primary lining case and the full overburden assumption is increased in frequency. Perhaps this minor trend reflects attachments to the old hypothesis that long-term creep of any geological material eventually results in null shearing strength.

5.4 *Pore water pressures*

With respect to the effect of pore water pressure on the behaviour of the soil (Figure 35), it is somewhat surprising to note that the water pressure on the lining is taken into account by only 41% of the answers.

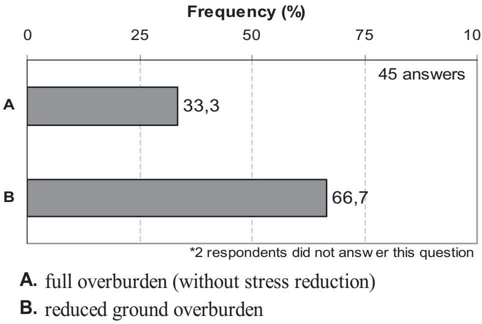


Figure 32. Overburden load assumptions on primary lining.

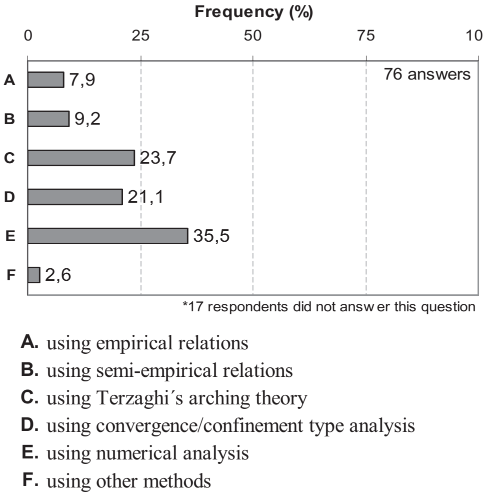


Figure 33. Methods for estimating the ground overburden reduction.

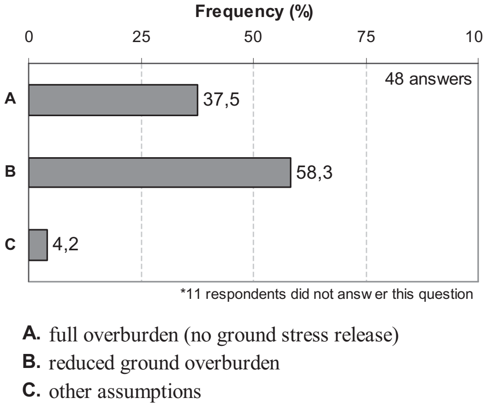


Figure 34. Overburden load assumptions on secondary lining.

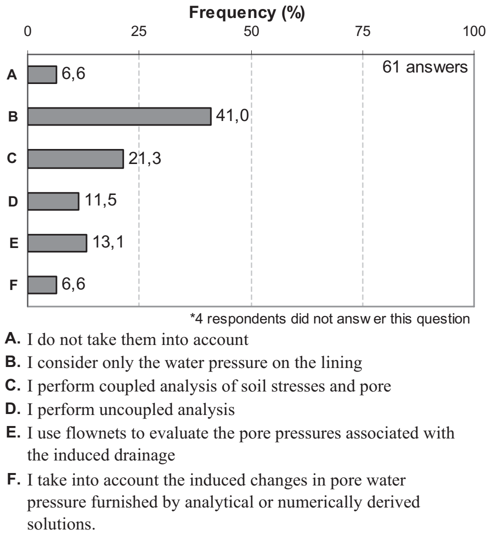
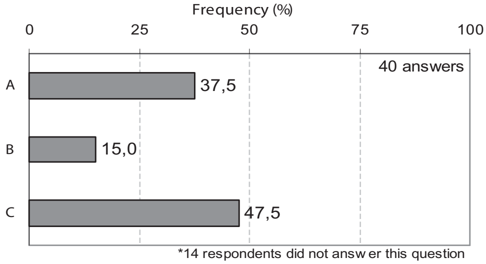


Figure 35. The effect of pore water pressure on soil behaviour.



A. I do not take it into account: I assume the soil mass as fully drained
B. I assume the soil mass fully drained and consider the seepage forces
C. I take into account the pore pressures and effective stresses (reduced or not)

Figure 36. Account of groundwater loading on the primary lining in tunnels below water table.

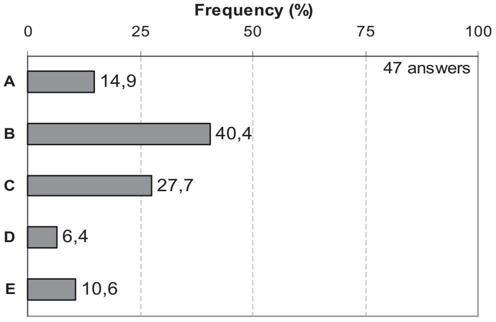
Figure 36 presents how practitioners take into account the groundwater loading onto the sprayed concrete primary lining of conventional tunnels below the water table. It is interesting to note that more than a third of the answers indicate they assume the soil mass totally drained and neglect any water pressure acting on the lining.

5.5 *Numerical modelling*

Concerning stress-strain analyses, the questionnaire focuses on the type of finite element analysis (2D or 3D) and the soil models. The use of 2-D finite element or finite difference models is now widespread, and codes have pre-processors specifically designed for the simulation of tunnelling. More recently, 3-D models, adapted to geotechnical problems, have been developed and are commercially available.

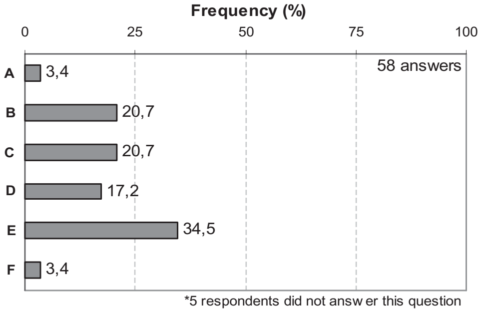
Despite the fact that the ground stress redistribution around a tunnel heading is essentially three-dimensional, Figure 37 shows that 55% of respondents rarely or never perform 3-D analyses. This can be explained by the fact that 3-D analysis is still a very time-consuming engineering exercise. On the other hand, it is promising that the remaining 45% of the respondents perform 3-D analyses 'sometimes' to 'always', something that would not have been seen a decade or two ago. Also promising is the fact that those who always perform 3-D analysis are consultants, a sign that this tool is increasingly being used in practice. No correlation was found between use of 3-D models and tunnel diameter, and thus size of the project.

It should be interesting to review these figures in a few years time, as the development of effective pre—and post-processors in 3-D numerical codes may lead to a wider use of 3-D modelling.



A. never
B. rarely
C. sometimes
D. often
E. always

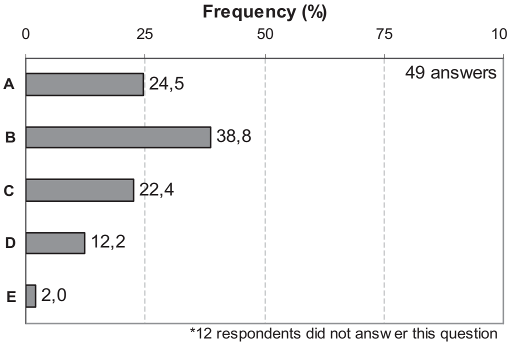
Figure 37. Use of 3-D stress-strain analyses in tunnel projects.



A. I do not use numerical methods for these purposes or I do not use 2D numerical analyses.
B. I consider a ground stiffness reduction.
C. I consider an imposed tunnel convergence (displacement boundary condition).
D. I consider a progressive tunnel core removal.
E. I consider a ground stress reduction in the tunnel perimeter.
F. none of above

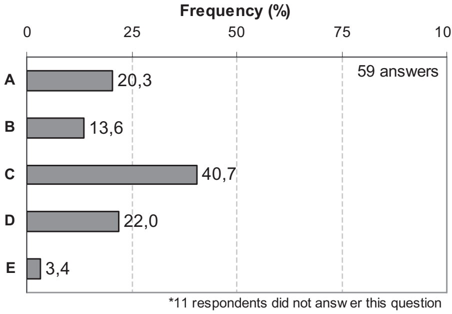
Figure 38. Account of 3D effects in plane-strain analyses to estimate ground settlements and lining loads.

Bearing in mind that 2-D analyses are still used more than 3-D, the survey investigated how three-dimensional effects are accounted for in estimating lining loads and displacements, when using plane-strain analyses in practice. Figure 38 shows that the procedure most used, as indicated by more than a third of answers, involves a ground stress reduction around the tunnel perimeter. The next most popular approach is to use an imposed displacement boundary condition in which the transformation from the 3-D problem to the simplified 2-D section is achieved by progressively simulating



A. solid finite elements
B. solid finite elements and shells
C. shell elements plus bars or springs
D. finite differences
E. boundary elements

Figure 39. Three-dimensional numerical analyses used for tunnel design.



A. consider the two layers of concrete working together
B. consider the two layers of concrete working separately
C. consider only the second layer of concrete (the secondary lining) and neglect the primary layer
D. assume a partial decay of the primary lining
E. make other assumption.

Figure 40. Account of layered construction in the design of reinforced concrete lining.

a volume loss over the tunnel section, and finally installing the lining. Note that the other remaining methods have also a similar and significant use by 17 to 21% of respondents.

Whichever approach is chosen, the problem remaining is the assessment of the degree of reduction of either ground stiffness, ground stress or tunnel volume, which means that going from a 3-D analysis to 2-D is not a rigorous process. None of the methods in use can be regarded as superior, as they all depend on user experience. Because of the diversity of these 2-D approaches, it would be interesting in the future to investigate how the reduction factors are assessed in practice to simulate successive stages of excavation.

Whenever a 3-D analysis is used in practice (see Figure 39) preference is given to the use of solid finite elements to represent the ground and shells to represent the lining.

In conventional tunnelling the primary and secondary lining are installed separately in time and eventually with different specifications.

The survey questioned how practitioners account for this layered lining construction in the reinforced concrete lining design (Figure 40).

It was noted that in the majority of cases only the second layer of concrete is taken into consideration and the primary lining is fully neglected, a very conservative and frequent assumption. On the other hand more than 40% of the answers indicate that respondents consider the two layers of concrete working together, sometimes assuming a partial decay of the primary lining, perhaps a more realistic hypothesis.

6 GROUND INVESTIGATIONS AND MONITORING

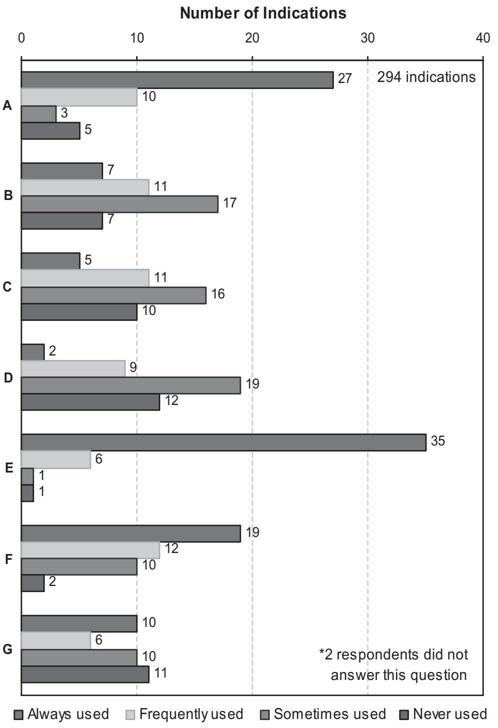
Practitioners were also invited to share their preferences regarding field and laboratory geotechnical investigations in their routine practice. In a 0 (never use) to 3 (always use) scale they had to show their preference regarding each investigation type. The results obtained are depicted in Figure 41.

It can be noted that soil characterization tests in the laboratory are almost always performed as much as Standard Penetration Tests (SPT) are performed in the field. However, plate bearing tests, dilatometer and pressuremeter tests are not used much in routine practice.

With respect to field monitoring Figure 42 shows that more than 70% of respondents indicated that it is always used in routine projects, and less than 9% never or seldom use it. This seems to reveal that practitioners are usually concerned about the risks involved and any damage potentially caused by their works.

Another question posed to respondents was whether they have been involved in the analysis of the monitoring results. 89% of respondents answered yes to this question, showing that there is no longer a strong “dichotomy” between designers and site engineers.

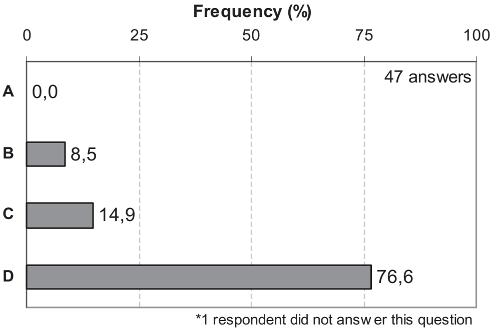
Types of monitoring equipment preferred (Figure 43) are still very traditional: levelling of surface markers and settlements points on buildings; convergence measurements inside the tunnel and pore-water pressure indicators (e.g. piezometers) are the most frequently used techniques. On the other



*2 respondents did not answer this question

A. SPT or SPT-T (with torque measurement)
B. CPT, Deep sounding
C. Marchetti dilatometer (DMT) or pressuremeter tests
D. plate bearing test
E. soil characterization tests
F. special laboratory tests on intact samples
G. others

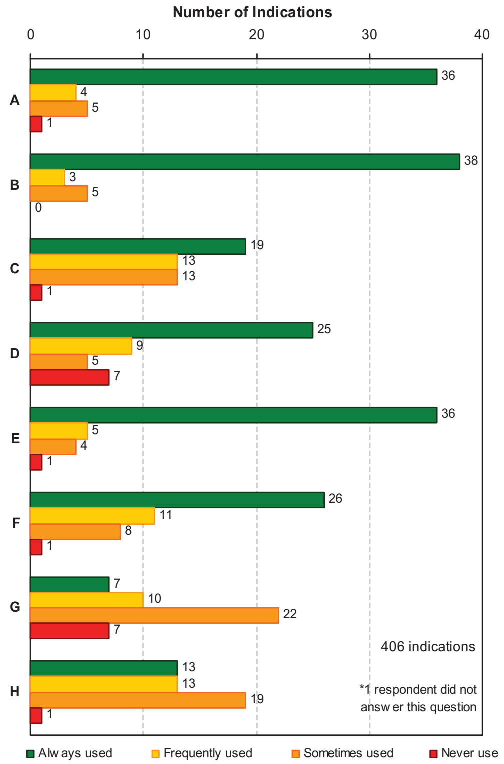
Figure 41. Preferences regarding geotechnical investigations.



*1 respondent did not answer this question

A. I never specify or never use
B. I seldom or rarely use
C. I frequently specify or use
D. I always specify or always use

Figure 42. The use of field instrumentation.



*1 respondent did not answ er this question

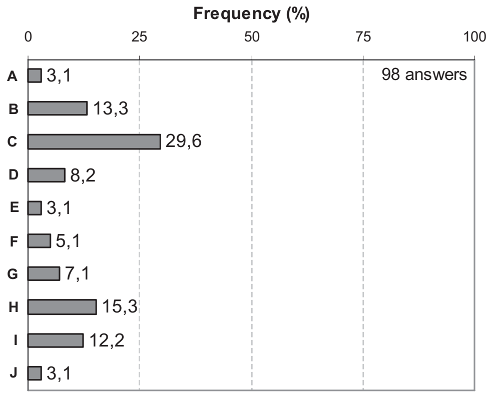
A. levelling of surface points (greenfield or near-greenfield)
B. levelling of settlements points in surface structures
C. levelling of deep settlement points
D. levelling of settlements points in the lining
E. convergence measurements
F. piezometers or water level indicators
G. load cells, stress or strain meters in the lining
H. inclinometers or slope indicators

Figure 43. Types of monitoring instruments.

hand, measurements of loads, stresses or strains in the tunnel linings are far less common.

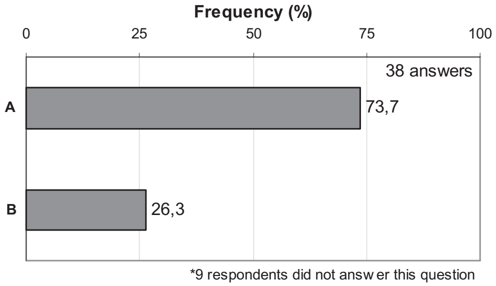
Figure 44 shows that the most popular way of transmitting instrumentation results (almost 30% of the cases) is to send it by e-mail. Note that more than 40% of answers refer to more up-to-date forms of data publishing (E to I), including use of more elaborate databases that seems to be becoming more widespread.

Another point addressed in the survey was reflected by the question: if real-time monitoring was implemented, was the excavation process, the ground reinforcement, the tunnel lining or other processes continuously adapted to the monitoring results? As shown in Figure 45, 74% of respondents replied that monitoring in real time is widely used for continuous adaptation of works. This is an encouraging result, since monitoring is not only



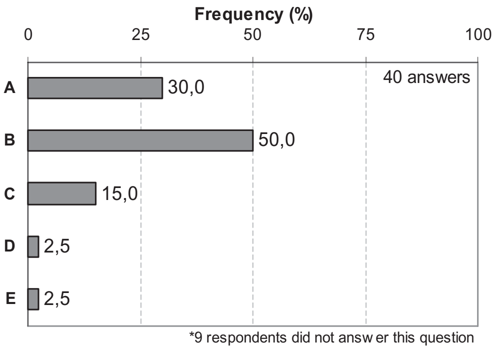
A. site only
B. paper reports faxed to other offices
C. emailed
D. shared on a VPN or FTP site
E. mounted statically on a website
F. mounted automatically on a web site
G. data sent to a web database server
H. data sent to a web database server with graph and reporting front end
I. data sent to a web database server with graph and reporting front end and GIS display
J. other

Figure 44. Forms of reporting field monitoring data.



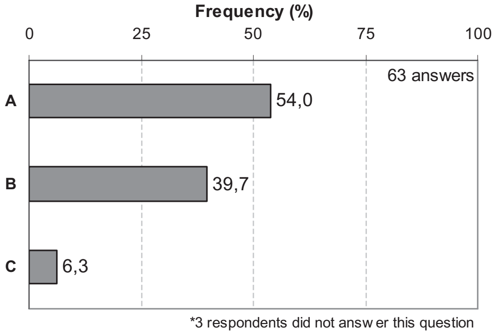
A. yes -
B. no -

Figure 45. Continuously adaptation of the excavation process, the ground reinforcement, the tunnel lining or other processes considering real time monitoring results.



A. less than 1%
B. between 1% & 2%
C. between 2% & 4%
D. between 4% & 6%
E. between 6% & 8%

Figure 46. Costs of geotechnical site investigation in relation to the total cost of the project.



A. performing deterministic analysis with average ground properties and using adequate factors of safety.
B. performing deterministic analysis with "worst" case assumptions and using adequate factors of safety.
C. performing probabilistic analysis, assessing or not a probability of occurrence of an event.

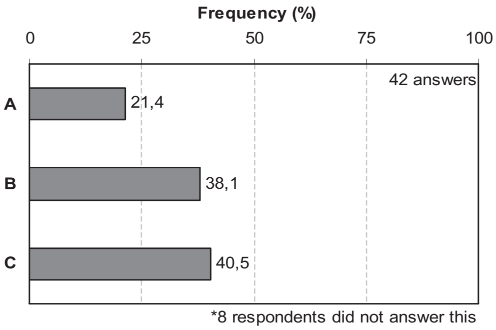
Figure 47. How variability and uncertainty of geotechnical parameters are accounted for in the design.

being used to check the performance, but is also used to optimize tunnel construction (by either increasing or decreasing tunnel support).

Regarding the costs of the geotechnical investigations in relation to the total costs of the projects (see Figure 46), it was noted that in 50% of the cases it ranks between 1 to 2% and in 30% of the cases it is below 1%, fairly low ratios possibly explained by the magnitude of costs associated with the larger tunnels and projects that are often represented in the survey.

7 RISK ASSESSMENT

It is interesting to note (see Figure 47) that probabilistic analyses are very infrequently performed, preference being given to more traditional deterministic approaches. This seems somewhat in



A. the owner employs a third specialised organisation to undertake the risk assessment
B. the risk factors are considered during the design stage, but no specific risk assessment is prepared
C. others

Figure 48. Approaches to risk assessment.

conflict with the perception discussed earlier that practitioners are usually concerned about the risks involved in urban tunnelling and about damage potentially caused by their works.

When asked about risk assessment as part of the design of the tunnel, 83% of the respondents confirmed that some element of risk assessment is always performed in their practice. On the other hand, for the implementation of these assessments in the tunnel design, frequently specific approaches are used, as indicated by Figure 48.

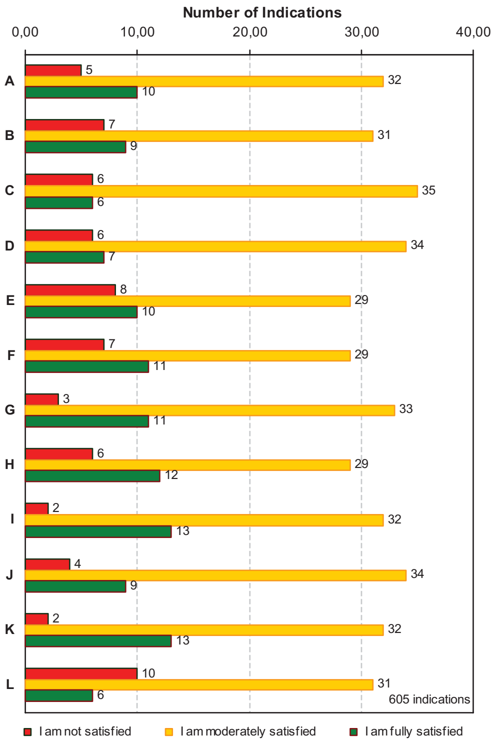
Combining the last two findings, one can speculate that practitioners do not perform probabilistic analyses in practice either because they are not familiar with the subject or because they do not have the resources to do so.

8 SATISFACTION WITH PRACTICE

Finally, the survey investigated the areas where practitioners are not satisfied with the current state-of-the-practice and understand that developments are required (see Figure 49).

The largest satisfaction levels were found with the current tunnel construction methods and with the lining types available. The least satisfaction levels were detected in the area of tunnel water-proofing which also showed one of the highest ratios of disapproval to approval levels with existing practice. In broad terms, respondents have shown to be moderately satisfied with all aspects investigated.

An evaluation of the practitioners' global satisfaction was calculated by the sum of all evaluated items shown in Figure 49, where the value zero was assigned for not satisfied answers, one for moderately satisfied and two for fully satisfied.



A. tunnels stability analysis
B. soil-structure interaction & deformation analysis
C. Face stability
D. settlements and induced damage estimates
E. estimates of lining loads and structural design of the lining
F. pore pressures and water flow estimates
G. field monitoring
H. field or laboratory investigations
I. available construction methods for tunnels
J. available methods for ground improvement
K. available types of lining
L. available types of water proofing

Figure 49. Satisfaction with the current practice.

Considering a total of 12 items, the maximum satisfaction with the current practice would ideally get a 24 mark and the minimum zero.

A correlation attempt was to relate the total satisfaction as defined above, with the recent experience of the respondents directly measured by the total number of tunnel designs each respondent conducted over the last five years. This correlation is presented in Figure 50. It appears that experienced tunnel designers are slightly less satisfied on average than designers with less experience.

However, it is worth noting that outlying points A and B are responsible for the negative linear correla-

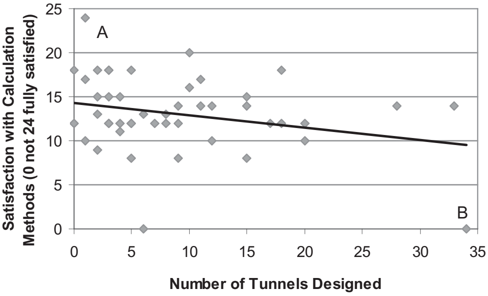


Figure 50. Comparison between total satisfaction degree and designer's experience.

tion shown. If these points were excluded it could be concluded that this correlation may not exist.

9 FINAL REMARKS

This survey focused on underground openings of any shape with more than 0.5 m diameter and covered many tunnel projects from around the world. The questionnaire was sent to geotechnical engineers, geologists, structural engineers and experts in numerical modelling, involved in the design or in the design supervision of tunnel projects over the past few years.

It is noteworthy that most of the professionals involved are related to tunnel consulting and construction and that the response was concentrated in Europe with no participation of professionals from Africa or North America.

The conclusions found refer to the most frequent practice scenarios representing the experience of the respondents. The scenarios are defined in broad terms by the respondents as covering: large size tunnels, with equivalent diameter larger than 6 m, designed for railways, metros, highways, driven under mixed face condition, in cohesive soils and soft rocks, below water table using sprayed concrete as lining (conventional tunnelling).

The assessment indicates that the design of conventional tunnels is conducted more rigorously than that for mechanized tunnelling, with the regard to the specification of construction procedures.

It was also noted that practitioners are concerned with the closure of the primary lining invert at a certain distance behind the face, for reasons of stability, quality of the lining and in order to control settlements. For face stability control, the preferred method is face nailing. The use of forepoling with driven steel piles is indicated to be the least preferred, despite being a popular technique in the 1970s.

The lining type most frequently used in mechanized excavations with a shield is bolted concrete segments. For conventional excavation, the most frequently used primary lining type is wet-mix sprayed concrete and for secondary lining, there is a preference for cast-in-place concrete.

There is a high frequency in the use of limit equilibrium methods and of empirical methods to assess the stability of the tunnel heading and face, although it is recognised that these approaches may not be accurate.

The use of numerical methods (FE or FD) is widespread in the local practice for estimating settlements or for tunnel lining design. Equally widespread is the assumption of reduced ground overburden in 2-D tunnel models. However, the persisting practice of using Terzaghi's arching theory to estimate the reduction of geostatic stresses is unjustified as it is potentially unsafe.

Due attention is being considered in practice to potential damage caused to surface structures, including preliminary assessments of sensitivity of these structures.

When designing primary and secondary lining the reduced overburden assumption is adopted by most, but the full overburden is also used by a significant number of the respondents, indicating possibly some prevalence of the questionable hypothesis of long-term creep of geological material eventually leading to zero shearing strength.

The majority of tunnel designers take into account pore water pressures, but this is often limited to accounting only for the effect of pore-water pressures on the lining. However, for primary lining, it is significant the amount of respondents who consider a fully drained situation.

A simplistic and incorrect hypothesis of ignoring the primary lining when the secondary lining is designed should be reconsidered. It should be possible to simulate and design linings taking into account both layers working separately.

The most used constitutive models in numerical analysis are those with elastic-plastic behaviour and a Mohr-Coulomb failure criterion. These models when applied to tunnels built with limited relaxation of ground stresses, resulting from restrictive construction methods, used to inhibit ground movements and associated damage in an urban scenario, result in linear elastic soil responses, with inhibited or limited plastic zones. This does not represent the now well-known non-linear behaviour of soils even at small strains: there is a clear need to use more appropriate and adequate soil models in local practice.

The use of three-dimensional modelling in practice is still limited, but it is believed that the increased use of this type of modelling, will be seen in practice soon.

A poor practice in geotechnical investigations for tunnel design was noted. It tends to be limited to soundings with SPT blow counts and simple laboratory testing on disturbed soil samples. This may be because of the emphasis on urban tunnels in environments which are, in general, well known both in geological and geotechnical terms, for which sizeable data banks are available. Perhaps a way to compensate such a deficiency is to stimulate the use of more sophisticated in-situ tests such as cone penetrometers, pressuremeters, dilatometers and others.

It is noteworthy that operating parameters are commonly monitored in shield tunnel projects, as they can be used as preventive measures to avoid excessive soil loss.

A favourable situation is seen in practice, in terms of field monitoring. Field instrumentation is always present. The noted deficiency is the lack of measurements of lining loads. There are a number of procedures to assess loads in concrete linings that could be used with variable degrees of success and cost but these are seldom used in practice.

Another important finding is that monitoring results are frequently used for the continuous adaptation of the excavation process, optimizing the tunnel lining and ground reinforcement.

Probabilistic analyses are still used very seldomly, preference being given to deterministic approaches, which is currently considered more traditional and conservative. On the other hand, risk assessments are often performed for tunnel projects.

Overall, respondents were found 'moderately satisfied' with current design and construction practice for tunnelling projects. However, the respondents believe that the area in need of further technical development is that of available techniques for water proofing tunnels. Nevertheless, they seem satisfied with the available construction methods and lining types. The survey indicates areas in current practice where academic institutions may contribute significantly to technology advancement.

ACKNOWLEDGEMENTS

This survey was only possible thanks to the kind attention of all those who replied the questionnaire. The authors acknowledge all of them and thank them for the time invested in the replies. They are: Pal Gyorgy, Alejo Oscar Sfriso, Roberto Terzariol, Mayer Zublin, Andrea Sciotti, Johannes Jäger, Enrico Maria Pizzarotti, Andreas Werth, Massimo Marchettini, Alessandra Sciotti and Andrea Pigorini, Yoshihiro Terashima and Hiroshi Dobashi, Takaaki Nishimura, Tomomi Iura, Thomas Böhme, Adri Vervuurt, R.W. den Hertog, Predrag Jovanovic, Stavroula Schina, Carlos Takashi Mitsuse, Sallo van der Woude, Erik Taffijn, IMM—Ingenieurbüro Maidl GmbH & Co. KG, Didier Subrin, Luis Eduardo Sozio, Daniel Scott, Alain Guilloux, Freyer Rudolf and Bayer Franz, Jacques Robert, Ana Cristina A. Hatori, Claudio Casarin, Fernando Stucchi, Marcelo Massaki Matsui, Werner Bilfinger, Arsenio Negro, Linn Nordstrom, Ernst-Rainer Tirpitz, Antonella Antonelli, Max Kitson, Thomas Lam, Johnny Cheuk, Dazhi Wen, Eric Chui Hon Man, Bai Yun, Gang Zheng, Saeid Khazaei and George Dounias.

REFERENCES

Bjerrum, L. (1963): Discussion to European Conf. On Soil Mech. Found. Eng. (Wiesbaden), Vol. II, p. 135.

Boscardin, M.D. & Cording, E.J. (1989). Building response to excavation induced settlement. *Journal of Geotechnical Engineering*, *ASCE*, 115, 1, pp. 1–21.

Burland, J.B. & Wroth, C.P. (1974). Settlement of buildings and associated damage. *Conf. on Settlement of Structures*, London, pp 611–654.

Mair, R.J., Taylor, R.N. & Burland, J.B. (1996): Prediction of Ground Movements and Assessment of Risk of Building Damage due to Bored Tunnelling. *Proceed. Intl. Symp. Geotechnical Aspects of Underground Construction in Soft Ground*, London, UK, pp. 713–718.

Negro A. (2008). Urban Tunnels in Soil: Review of Current Design Practice in Brazil. *The 6th International Symposium on Geotechnical Aspects of Underground Construction in Soft Ground*, Shanghai, China, pp. 640–645.

Negro, A. & Eisenstein, Z. (1997). Delayed Lining Activation and Ground Stress Relaxation in Shallow Tunnels. *Proc. of The 4th Intl. Conference on Soil Mechanics and Foundation Eng*, Hamburg, Germany, pp. 2391–2396.

Negro, A. & Leite. R.L.L. (1995). Design of Underground Structures in Brazil—National Report on Tunnelling and Braced Wall Excavation in Soft Ground. *Proc. Intl. Symposium on Underground Construction in Soft Ground*, New Delhi, India, pp. 49–56.

Skempton, A.W. & Macdonald, D.H. (1956). The allowable settlements of buildings. *Proc. Inst. Civ. Eng.* Part III 5, 727–768. Discussion closure: 783–784.