www.tunnellingjournal.com
Dec 2016/Jan 2017

Tunnelling journal

The international journal for the tunnelling industry

SEE PAGE 8

THE TBM EVOLVES

TJ DISCOVERS A SEA OF CHANGE COULD BE ON THE HORIZON FOR THE TBM SECTOR

SEE PAGE 26

SCANNING SYSTEMS

A LOOK AT SOME OF THE NEWER TECHNOLOGIES AVAILABLE TO THE TUNNELLING ENGINEER

SEE PAGE 36

SPECIFY TO SUSTAIN

MATERIALS THAT CAN HAVE A HUGE IMPACT ON YOUR PROJECT'S SUSTAINABILITY

BREAKTHROUGH OF THE HERRENKNECHT MULTI-MODE TBM S-769 IN A CAVERN BELOW RIO DE JANEIRO IN APRIL 2016

Overview of technology in today's tunnelling projects

In this article, Benoit Jones looks at new technologies being deployed in recent tunnelling projects, what makes a good innovation and what are the barriers to adoption of new ideas.

IN THE OPENING sequence of 2001: A Space Odyssey, one of our ancestors picks up a large animal bone while listening to Richard Strauss's Also sprach Zarathustra and realises he can use it as a weapon. He then uses it in a face-off with another group, killing one of them and scaring off the rest. The scene ends with him throwing the bone into the air. The next thing we see is a spaceship orbiting the earth to the tune of the Blue Danube waltz.

In doing this, Stanley Kubrik is drawing a line from our first use of tools to an advanced society that can travel into space and do things that would be unimaginable to our Palaeolithic great grandparents about 2.6 million years ago, or even to Richard Strauss in 1896 when he wrote his epic tone poem. He is tracing the history of technology.

Technology can be defined as anything made or used as a tool. It doesn't even have to be a thing, probably the most powerful technology ever developed is language. Language, writing, printing, telephones, computers and the internet enable us to share ideas and collaborate. So often technology can't be viewed in isolation, but it is part of an ecosystem that co-evolves. Humans also have literally co-evolved with technology, allowing us to leave Africa and colonise less hospitable parts of the world, to diversify and specialise.

Technology allows us to fulfil our potential – Kevin Kelly asks us to imagine what Mozart's life would have been like if he had been born before the piano or the violin were invented (Kelly, 2005). Or any of us without language. There are children being born today whose lives will be occupied by inventions we haven't yet conceived of.

Therefore, we can understand why the musical technologist, inventor and artist Laurie Anderson said, "Technology is the campfire around which we tell our stories". We are inseparable from technology, which has co-evolved with us, and shaped us as much as we have shaped it. It is part of who we are.

Nowadays, however, we often understand 'technology' to mean a new gadget, usually electronic. According to this usage, something well established and reliable, say a pocket calculator, maybe would only be described as technology in a history lesson about the 1970's. The idea that technology is cutting edge but not yet bug-free led Douglas Adams to describe technology as "something that doesn't work yet" and we all know what he means.

How do new technologies come about?
An idea is a network, literally a new configuration of neurons in our brains. An innovation, being a new idea, is therefore a set of connections, connecting a new arrangement of things or concepts. Thus, innovation rarely comes from "special people in special places dreaming up creative ideas, out of the box", but from "combining the talents of lots of people, often borrowing and developing the ideas, collaboratively, in the cause of solving a difficult problem" (Leadbeater, 2005). It is also very rarely a completely new thing, it is usually a combination or repurposing of existing technologies.

But innovation is not just about having great ideas and generating prototypes. It is also about understanding how consumers will incorporate the technology into their lives and developing an affordable and sustainable business model for achieving that.

What makes a good innovation?
Rachel Botsman says that a good innovation is one which addresses a pain we experience (Botsman, 2012). How much the innovation improves our lives determines how much we will be willing to pay for it, and how much effort we will be willing to put in to incorporate it into our lives. If there is no pain to address, then there is no point to the

innovation. Usually this pain is one of the following:

1. Price
2. Time/Convenience
3. Safety/Health
4. Quality
5. Environmental (for those of us who care about the environment)
6. Uncertainty

We can probably all think of areas of our working lives where we experience pain – something we have to do that is time-consuming, costly, boring, has risks we can't reduce or remove, or results in a product that isn't of the quality we ideally wish it to have. Sometimes we are not aware of the pain, until someone comes along with a solution and we wonder how we put up with it before! We weren't aware that we lacked mobile phones, but once we got used to them it became hard to imagine getting by without them. This is because we adapt to new technologies and incorporate them into our lives.

Another trend identified by Botsman (2012) and by Warburg (2016) is that the way we trust is changing. Increasingly we favour systems that allow us to verify information for ourselves rather than trusting corporations or institutions.

Where do we experience pain in the tunnelling industry?

This would be a good area for a questionnaire! Some ideas I've had, plus some that have come from discussions with friends in the tunnelling industry are:

- Cables
- Things that don't just work off the shelf
- Not getting information in the format you need – needing to process data manually, sometime multiple times for different purposes
- Knowing you have excavated or sprayed the correct profile in a sprayed concrete tunnel
- Survivability – how often things we use or install die
- Reliability – how often things we use or install need to be repaired or re-baselined
- Installation time
- Insufficient accuracy or poor repeatability
- Lack of integration of different systems
- Uncertainty

Uncertainty is a big factor and often means risk to health, safety, environment, quality, programme or budget. Often uncertainty results in an increase in cost as we build in redundancy. An innovation that reduces uncertainty can therefore be of significant value even if it is costlier or takes more time, as it will reduce risk and may reduce over-design.

In the following sections, we will look at some of the newer technologies that are currently being used in the industry, and assess them against the pains they reduce or remove, or to take a more positive view, the value they add. Due to space constraints, only 2 main areas will be considered: positioning, setting out and as-built surveys, and monitoring during construction for design verification.

Positioning, setting-out and as-built surveys

In all kinds of underground space we almost always use a laser total station for primary survey control, with prisms or bireflex targets. In conventional tunnelling (i.e. not TBM), the excavation profile or the as-built sprayed concrete lining profile can be measured using a reflectorless total station, but lots of points need to be shot and there remains uncertainty about what happens between the points.

One solution that has been around since approximately 1998 is the use of photogrammetry (Dibit, 2016). Overlapping digital photographs taken from different angles can be analysed to measure distances to a surface, with a global accuracy of ± 10mm and a profile accuracy of ± 5mm. For the purpose of assessing the excavation profile or sprayed concrete thickness, this accuracy is perfectly adequate. According to the brochure for the Dibit FSC 5100 SRsF1, set up and measurement of the profile can be achieved in about 1 minute.

For about the last 10 years, laser scanning systems have also been available. These are sometimes referred to as 'LiDAR'. These work in a similar way to a reflectorless laser total station with electronic distance measurement, but are set up to take between tens of thousands to over a million measurements per second, to provide point clouds of 3D coordinates. There are several suppliers of this technology, with Dibit Messtechnik and Amberg Technologies providing tunnel-friendly versions with accompanying software to aid workflows.

Laser scanners come in two flavours: stationary/spherical and kinematic/radial (Schneider et al., 2013). Stationary/spherical means the scanner is positioned on a tripod and scans in all directions. A kinematic scanner is mounted on a vehicle or trolley and rotates on one axis, continuously recording a helical point cloud.

Kinematic scanners, since they are mostly shooting to a perpendicular surface, have better relative accuracy, but rely on positioning methods for their global accuracy, which typically involves high-end total stations tracking a prism mounted on the vehicle in combination with inertial sensors measuring orientation of the device. Absolute accuracies of a few mm can be achieved in optimal conditions, according to Schneider et al. (2013). 'Optimal conditions' usually means pushing a cart along railway tracks or a smooth roadway. For condition surveys or kinematic envelope surveys of operational tunnels, this method is faster and more accurate than using overlapping stationary surveys.

Stationary scanners are better for scanning an excavation (Figure 1), as the face and the excavated profile can be scanned at the same time. Positioning can be achieved by including fixed points in the image (known as 'pass points'), which can be either spheres or black/white targets, and by using a total station to find the position of the scanner by shooting to a prism mounted on it. Global accuracy of about 10mm is possible.

Both kinematic and stationary laser scanners can also include a digital camera. The digital image is then stretched onto the point cloud. Most high-end laser scanners on the market include this capability, e.g. Leica's ScanStation P40. Dibit have a hybrid of photogrammetry and laser scanning system available, using multiple digital cameras. This is brilliant for condition surveys of existing tunnels (Figure 2), and is also of interest in mapping the geology and geometry of the tunnel face at the same time.

Figure 1 (above): A stationary laser scanner for tunnel profile measurement (www.ambergtechnologies.ch)

Figure 2 (right): Kinematic laser survey at Biel-La Huette using Dibit LSC 4200-MRF in 2013 (www.dibit.at)

For verifying the excavation or sprayed concrete profile, then, laser, photogrammetric or hybrid scanners appear to be a very useful tool that should improve productivity and provide more complete assurance of quality. They can also provide an accurate record of geology, that can be processed by software. Whether they add value overall will depend on a project's attitude to cost and quality.

For condition surveys and kinematic envelope surveys, the use of kinematic hybrid scanners is highly efficient. A person doing a condition survey the old way, with a clipboard and camera, will struggle to do a detailed survey of 100m of tunnel in a nightshift, and they will get a neckache, or fall off the walkway as happened to me once. But with these new technologies, an accurate and detailed geo-referenced record of the condition can be obtained, of probably up to 1,000m length of tunnel in a nightshift. Therefore, spending on equipment is offset by big improvements to productivity and accuracy.

These methods also address trust, in that they allow clients or other stakeholders to verify the data for themselves.

Monitoring during construction for design verification

Due to the assumptions we make in design about what are inherently variable materials (rock, soil, concrete…) and uncertainty about the true ground mass behaviour, we need to monitor underground construction to ensure it is behaving within the expected limits of the design and hence is safe. We mostly do this through monitoring ground movements (mainly surface settlements but sometimes in the ground as well), and monitoring displacement of the lining.

Lining displacements are currently measured, on the vast majority of projects today, using a total station and prism or bireflex targets installed in the tunnel lining. There are a number of problems with this, one being poor survivability of targets, and the other being the time between installing the lining and taking the first reading, which is often between 8 and 12 hours (Clayton et al., 2006).

While monitoring lining displacements tells us qualitatively that an equilibrium has been reached, or alternatively they might indicate that very bad things are about to happen if we don't act soon, they don't tell us what the factor of safety is. It is theoretically possible to use lining displacements to calculate average axial strains between targets, or even bending strains if curve-fitting between multiple targets is used. But then the problem is that strains are not particularly useful in assessing the safety factor of a tunnel lining, which is based on stress. Another issue is the accuracy of the measurements. Using best practice total station surveying methods, it is likely that accuracy of convergence monitoring is ± 2-3mm. So even if the lining could be assumed to be linear elastic with Young's modulus of 20GPa, this means the error in calculation of strain in a 10m diameter tunnel will be 200-300 microstrain, leading to an error in stress of ± 4-6MPa (Jones, 2007). If you halve the diameter, the error doubles.

200-300 microstrain, to put it in context, is of a similar order of magnitude to the strain due to ground loading in a reasonably shallow tunnel, and also similar to the magnitude of plastic strain, shrinkage strain, thermal strain and creep strain in concrete.

One approach often used is to assume that if the measured lining displacements are similar to the ones predicted by the design model, then this is sufficient verification. But this is only true if the assumptions made in the design model about the stress-strain relationship, plasticity, creep, shrinkage and thermal expansion and contraction, all of which change with maturity of the concrete, can be proven to be valid. Otherwise the displacements could be the same, but the stress could be very different.

Figure 3 (left): One of several multicore cables required for 2 arrays of instrumentation (pressure cells and strain gauges) installed at Heathrow Terminal 4 station in 1996 (photo taken in 2015)

Figure 4 (above): Installation of a radial and tangential pressure cell in a sprayed concrete lining

For concrete linings, the rate of flow method (England & Illston, 1965) allows the back-calculation of stress from a history of measured strains, by removing creep, shrinkage and thermal strains and converting the resulting strain due to loading into a stress. However, obtaining strains from total station convergence measurements will result in considerable uncertainty in the results.

There are more accurate methods of obtaining strains, using strain gauges or tape extensometers, for instance. Strain gauges are disliked due to the time required for installation, and the cables and dataloggers required, as well as the time needed to analyse the data. Tape extensometers are disliked due to the need for access to the face area to take readings, which will impact on productivity.

A promising development is the increased use of fibre optic cables as strain gauges. There are two types: Brillouin Optical Time Domain Reflectometry (BOTDR), which gives continuous strain readings along the length of the cable, and Fibre Bragg Grating (FBG), which gives strain readings at specified points along the cable's length. BOTDR requires more expensive equipment than FBG. One advantage over conventional strain gauges is there is only one cable that can be almost any length, rather than needing 2 cables per strain gauge, a junction box and then a multicore cable(s) to a datalogger (Figure 3) Therefore, installation is probably faster and simpler.

So, there may be less painful ways of measuring tunnel lining strains. But remember that strains are not very informative on their own. Unless very good information is available for that particular concrete mix about its stiffness, stress-strain behaviour, plasticity, creep, shrinkage and thermal behaviour, and how those parameters change with maturity, and unless temperature is also being measured, these strains cannot be converted into stresses with any confidence.

Again, similar to displacements, it may be tempting to say that one could compare strains measured in the field with strains predicted by the design model, but even if they are the same this doesn't tell us the factor of safety of the tunnel lining. The stress, and hence the factor of safety, will only be the same if all the assumptions about concrete behaviour made in the design model are the same as in real life, and this also needs to be verified.

Another possibility is to measure stress using either pressure cells, which need to be installed within the lining and the cables hooked up to a datalogger (Figure 4), or to use a one-off type of measurement such as slot-cutting. Slot-cutting involves cutting a slot normal to the stress direction. The strain due to the relaxation of stress during slot-cutting is measured by strain gauges installed on the surface of the concrete. Then a flat jack is inserted into the slot and it is jacked up until the strains have been reversed. This is a robust and reasonably reliable method, but it only provides one data point. Pressure cells provide continuous measurement, but a lot of care is required in their installation and interpretation to get meaningful results (Jones, 2007).

The area of design verification is one where we experience considerable pain due to uncertainty, in the form of conservative design and poor understanding. The solutions are only partial and involve pains of their own. This is an area that really needs innovation.

Conclusions

Ideas are a network, and usually come about from people collaboratively combining different ideas to solve a complex problem.

Good innovations address pains we experience and provide a solution that is easy to adopt.

Uncertainty is a major pain in our industry, resulting in poor understanding of risk (uncertainty about the level of uncertainty) and conservative design.

Only by being honest about our uncertainties can we move forward in identifying areas that need innovation.

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