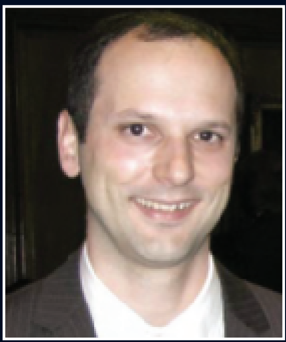

Resilience

In this article, Dr Benoît Jones, Tunnelling and Underground Space MSc Course Manager at the University of Warwick, UK, discusses resilience.

"RESILIENCE IS THE NEW SUSTAINABILITY" is a phrase I heard recently and immediately tried to forget but couldn't. This was at a 'sandpit' event, where academics get together to throw ideas for research around, find collaborators and target funding sources. The primary aim is to add value to society and the economy through relevant, timely and novel research. Winning research grants is highly competitive, and usually in response to 'calls' targeting certain areas identified by the government research councils. This results in a secondary aim, which is to hit the right notes in a proposal, which means using all the right buzzwords. One of these is 'resilience', which is one of those words that the more you think about the more complicated it is. And if you still read these columns then you must by now and agree that complicated = interesting.

So what is resilience?

Dictionary definitions for 'resilience' are similar to those for 'robustness', but its use in engineering has become more specific. Something that is 'robust' resists shocks and stays the same; it is immune to harm. It does not break, but neither does it benefit from shocks.

Something that is 'resilient' recovers quickly from shocks, but is not completely unaffected. The crucial aspect is that after an extreme event it retains functionality in the short term and is easy to repair. In a fire, a concrete tunnel lining containing polypropylene fibres may be resilient, but it is not robust. The polypropylene fibres may prevent explosive spalling and in most cases the tunnel lining will not lose its structural integrity, but some clean up or repair will be necessary in most cases. The crucial aspect is that the tunnel lining does not fall down, and use of the tunnel is only impaired for a short time. For a tunnel lining to be robust, it would need to be completely unaffected by a fire. Therefore, resilient is often more cost-effective than robust.

Some readers may be thinking that, the way I have defined it, robust is impossible to achieve. This is probably true, as the randomness of shocks such as earthquakes and fires mean that even the most robust structure will eventually succumb, even if it takes several thousand years for a sufficiently extreme event to occur. It is important, however, to remember that a 1 in 1000 year probability event could happen tomorrow.

The resilience of systems

As we have seen, perfectly robust infrastructure has yet to be invented. But infrastructure systems can be made more resilient if they have redundancy, are adaptable, are diversified and can exhibit self-organising behaviour. Large, interconnected systems are fragile, as we have seen in the economic crisis that began in 2008. If a large city were served by only one huge water treatment works, that would not be sensible. Similarly, if there is no redundancy or diversification in transport systems, a minor technical fault on one route can result in massive disruption across the network.

Very low frequency, but very high consequence risks are often either ignored or made negligible by multiplying the consequence by a very small value of likelihood in a risk analysis. This is a mistake, especially when the hazard is the weather or the economy, or where systems are interconnected to such a degree that it is not only the risks that you own that you should be concerned about. A probability based on past events seems to be a poor method of prediction, especially for hazards that are perceived to be low frequency but high consequence (e.g. the Fukushima disaster). Resilient systems need to be based on identification of hazard scenarios, as developed in Switzerland over the last 25 years (see e.g. Amberg, 2004) and measure fragility rather than risk. For every hazard, the consequences should be minimised by design and there should be an action plan to deal with it. If there is no way to deal with it and the consequences are important, then the system is fragile.

From this viewpoint, then, resilient systems are on the fragile side of robust. The best way to make a system more resilient is not to do more risk analysis, but to reduce fragility or susceptibility, because predictions of risk are not reliable.

Antifragility

Some systems, such as ecological and economic systems, thrive on frequent (but not too large) shocks. Each shock brings with it information that can be used to improve the system. Imagine if you never gave your body any shocks by living in a sterile, zero gravity environment with no intellectual challenges and no stairs to climb. You wouldn't last long. Humans, and all other living things, need a certain degree of volatility, which helps us stay healthy and be prepared for the larger shocks when they come. In a sense, 'what doesn't kill you makes you stronger'. The same applies to other complex, nonlinear systems, such as the economy, which relies on the constant feedback of volatility to provide information and small shocks to keep individual parts of the system fit and healthy.

There is also a sense in which systems become stronger when individual parts fail. Natural selection results in evolution. The same can be said for the economy, where the failure of less successful enterprises allows capital to be reallocated to more successful ones. Constant competition results in leaner, fitter companies, as it drives improvement and culls the weak. This is why organisations that are 'too big to fail' are a bad idea and probably shouldn't be allowed.

Naseem Nicholas Taleb (2012) invented the concept of 'antifragility' to describe these phenomena. Antifragility is the opposite of fragility, i.e. where harm does good. A continuum can be imagined from fragile (where shocks are harmful) to resilient (where some shocks can be absorbed and fragility is reduced) to robust (where neither harm nor benefit arises from shocks) to antifragile (where shocks are beneficial). Clearly being antifragile is more desirable.

Antifragile structures and systems

It is difficult to see how an engineered structure could ever be antifragile, since shocks above a certain level will always cause damage or fatigue, and the structure will not learn, become fitter or increase redundancy because of exposure to shocks or fluctuations in loading.

However, it may be possible to engineer antifragile systems. Taleb (2012) gives the example that every air disaster results in safer aeroplanes, because they are investigated, the knowledge disseminated, and improvements made. Continuous improvement is a way in which engineering as a whole can be antifragile. Due to the multitude of lessons from failure, structures today are much safer than they were in the past, and this is all down to learning lessons from failure. Forensic engineering is now an important part of the undergraduate and MSc curricula at Warwick and at many other universities (Mottram & Smith, 2012).

Embrace randomness and complexity

We should learn to embrace randomness. This is not a call to join me at the next Glastonbury Festival. Tunnels are never in a permanent state of equilibrium, as has been proven by stress measurements (Jones, 2005 & 2007) showing the variation of stress in a tunnel lining due to temperature, concrete shrinkage, creep and soil consolidation effects. Also, geology is variable. Even within a relatively homogeneous soil there will be variability of geotechnical parameters. We need to embrace and understand this variability, the scale of fluctuation and the impact this may have on design.

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As I have mentioned before, Negro and de Queiroz in 2000 reviewed 65 papers on numerical modelling of tunnels. Of the 55 papers that compared predicted maximum surface settlement with measured values, 39 of the predictions, corresponding to more than 70%, were within ±10% of the measured values. Shirlaw and Wen (2005) pointed out that natural variations in settlements are generally much higher than ±10%, and suggested that this contradiction may exist because few people would publish cases where the predicted and actual settlements were significantly different, or because 'predictions' may have been made after the event and adjusted to match performance. In addition, if settlements were measured at several locations, the 'typical' profile may have been selected carefully. This is a clear case of people not embracing randomness, in fact of obscuring it, which does no-one any favours; because variability in itself is something we need to know more about.

What we need to do is make more case studies publicly available. Not just the ones where everything behaved exactly like the computer said it would, but the imperfect data, the unexplained variations between different monitoring cross-sections. And no 'smoothing' of data to remove outliers, because there might be something interesting there that someone else might see. Also, the times when very little movement occurred or no movement occurred at all, which don't tend to get published because the curves don't match what the conservative prediction said, or are too flat to fit a Gaussian curve to. These would be very valuable to promoters of future projects. For instance, we hear all the time of CTRL and how wonderful it was at achieving low volume losses, but is any of it published?

Where do we go from here?

In the October/November issue of Tunnelling Journal, where I talked about competence, some of the ideas overlap. What is desirable are resilient structures and resilient or antifragile systems, where hazard scenarios are understood, are seen coming if possible, and can be dealt with, not apparently robust structures or perceived-to-be efficient centralised systems that fail unexpectedly and catastrophically.

A similar requirement is that we get the feedback required to learn from the randomness inherent in complex systems. Robust, fragile designs do not allow this to happen, and neither does the pretence that everything is predictable.

Site managers concerned about the safety of their workforce do all they can to find out about every near miss or minor incident, because they understand that these events provide important information and give them the opportunity to change the method of working before something serious happens. We need to take the same approach to the structures and systems we design and construct.

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