

RESILIENT GEOTECHNICS - PAST FAILURES AND FUTURE SUCCESS

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ABSTRACT

The concept of resilience applied to engineering systems has gained importance in recent years. Geotechnically, all infrastructure assets interact with the ground and so resilient geotechnical solutions must meet a range of plausible conditions including not only stability and serviceability, but increasingly, repairability, growing demands, climate change and impacts from surrounding works.

Resilience may be described as the ability of a system to adjust its functioning in response to changes while satisfying performance, economy and safety objectives. In the infrastructure engineering context, the notion of resilience can apply to fixed assets, but more perhaps more influentially it applies to the organisations that design, construct and operate those assets. This paper documents historic examples of geotechnical and other engineering failures where geotechnical resilience was deficient, and lessons learnt which can be used to increase resilience in future applications. Failures are reviewed in the lights of „traditional“ or „linear“ safety engineering concepts which include contributing factors such as people, processes and products. The evolution of safety engineering concepts is also examined by looking at improving risk management, design standards and construction processes towards Resilience Engineering (considering both assets and organisations), where risk is actively managed to achieve superior outcomes. Despite these advances over time, recent failures show that some of these lessons must be painfully re-learned; wisdom is difficult to teach.

Looking forward towards to achieving resilience in future infrastructure design, this paper considers global economic, social, and environmental factors which interact with the field of geotechnics, and how this discipline plays a role in creating robust, flexible infrastructure organisations and assets which are safe, secure, and resilient to what the future may hold. Examples of how climate change and changing societal needs may impact projects are discussed alongside future research trends and emerging geotechnical innovations such as Building Information Management (BIM) and performance based design.

Collectively, the failure examples, risk management guidance and Resilience Engineering concepts herein are provided so that geotechnical practitioners can benefit from case history learnings and can apply new tools to future geotechnical engineering challenges. By knowing what to do, what to look for, what to expect and what has happened (historically and in the project timeframe) then safe, reliable *and* efficient infrastructure can be created.

1 INTRODUCTION

The objective of this paper is to reflect on past, present and future engineering practices which respectfully weaken or enhance the creation of resilient infrastructure. In the context of this discussion, a useful definition of „Resilience Engineering“ is that proposed by the „father“ of the emerging field, Erik Hollnagel in his seminal publication *Resilience Engineering: Concepts and Precepts* (2006):

“The intrinsic ability of a system to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions.”

This definition implicitly includes the conventional definition of safety, whereby „*the ability to sustain required operations*“ may be seen as a requirement to satisfy ultimate (and serviceability) limit state requirements. This definition, however, also requires the ability to function under „*both expected and unexpected conditions*“ rather than merely just avoid failure. It is this ability that makes the system both safe and efficient, which in turn makes Resilience Engineering attractive and worth exploring.

The notion of resilience as a new systems approach to understanding of safety, risk and performance under competing economic and workload pressures is a relatively new concept with wide-ranging applications beyond geotechnical engineering including ecology, computer networks, economics and industrial / organisational safety. Only selected Resilience Engineering concepts are presented herein, alongside more traditional risk management concepts, illustrative case-histories and historical learnings as they relate to mainly geotechnical aspects of infrastructure design, construction and operation.

Considering the types of infrastructure challenges facing geotechnical engineers, it is worth noting that port and maritime engineers often face relatively high geotechnical risks compared to other forms of civil engineering due to sites being pre-disposed to soft and unfavourable ground with significantly fluctuating groundwater and tidal conditions and the frequent need for retrofitting / deepening old works, generally without existing drawings and with large failure consequences. For this reason, and also the author's experience bias and interest towards these projects, many of the following case histories have a maritime engineering flavour.

Ultimately all infrastructure assets interact with the ground and their integrity relies substantially on the performance of geotechnically designed elements. In terms of safety, the challenge is to create „tough“ rather than „brittle“ designs (and/or systems of work) which can adapt to, and absorb disruptions and disturbances, even those that fall beyond the capabilities that organisations or assets are trained or designed for (think: World Trade Centre). The future-proofing of infrastructure requires both training of practitioners and incorporation of resilient and reliable geotechnical components which can absorb future environmental changes, potential changes in use and/or impacts by other works.

The following sections focus mainly on geotechnical engineering challenges during design, construction and operation with the aims of reinforcing lessons learned from past failures and understanding how new tools and techniques can be used to create safe and efficient infrastructure.

2 FORMATIVE LESSONS IN EARLY ENGINEERING

On reflection, we are unfortunately spoilt for choice with historical examples of geotechnical and engineering failings, most of which provided hard lessons at the time for the developing engineering community operating on a largely trial and error basis. As drawings and texts became more widespread during the medieval period (5th to 15th century), the use of this written, transferrable knowledge helped to disseminate design concepts and facilitate construction of increasingly large scale and complex religious structures such as cathedrals and mosques.

In his informative paper „*How to design a cathedral: some fragments of the history of structural engineering*“, Professor Jacques Heyman (1992) describes how 13th century sketchbooks by Villard de Honnecourt show that cathedral building was anything but an amateur occupation. In that era, there was no distinction between architect or engineer; the head of such building projects was known as a „master of the work“, having completed a long, largely practical training regime from apprentice through journeyman and foreman.

Such masters had a firm grasp of both aesthetic „architectural“ design of Gothic and Renaissance styles and also technical aspects of masonry design including lining, levelling, plumbing and vaulting arrangements. Interestingly, the overriding view at the time was that it was the *shape* of the structure that governed its stability and hence the importance of geometry greatly overwhelmed that of theoretical stress calculation. Scaled models were also used as a test-bed for new or complex features, and to engage with project sponsors.

The bulk of surviving writings on ancient building design dwell on rules relating to geometry with, perhaps, an intuitive understanding of the resulting stresses. The results, however, align surprisingly well with modern structural engineering principles. Success on these early landmark projects depended on the relatively informal involvement of experienced craftsmen and women who could apply rules of precedence, empiricism and „well winnowed experience“ (Burland, 1987). In today's terms, this senior involvement has evolved into formal and auditable review processes.

Lasting examples of these impressive structures include the magnificent c.17 Ottoman Sultan Ahmed (Blue) Mosque in Istanbul, featuring the largest religious dome in the world, and the imposing Lincoln Cathedral in England which was commenced in 1088. The latter was reputedly the tallest building in the known world for over two hundred years between 1311 and 1549 until the spire embarrassingly toppled, following repeated previous failures in 1185 (earthquake) and 1237 (alterations), as described by Jarvis (2014). It is worth considering the advice from a scholar of the period, the 11th century philosopher Solomon Ibn Gabriol, whose reflections on life can be extended to contemporary engineering practice and the Resilience Engineering concepts herein:

“The first step in the acquisition of wisdom is silence, the second listening, the third memory, the fourth practice, the fifth teaching others”.

Understanding the evolution from these early trial and error approaches towards methodical design and construction using Resilience Engineering concepts, requires us firstly to reflect on the features and shortcomings of early landmark projects. These contain some fundamental lessons that our predecessors have benefitted from and which are equally important today. Examples and salient lessons from three case histories spanning the Medieval to Victorian periods are explored below. That they are all British may be due to the pioneering nature of UK constructions at that time and also that documentation of these projects during construction and following completion was more comprehensive than from similar projects in different parts of the world at that time.

St Davids Cathedral, Pembrokeshire, Wales (1181 onwards)

Nestled in a picturesque grazing valley, construction of the present Cathedral began in 1181. While specifics of geotechnical conditions are scant, the site is sloping and founded at least in part on alluvial soils adjacent to the Alun River. Anecdotal accounts (Lloyd *et al.*, 2004) indicate that foundation problems occurred at an early stage due to the terrain and „uncertain“ foundation conditions. No prizes, then, for identifying the first lesson (often since repeated) that rudimentary investigations, or even desk study and inspection by a seasoned geological eye, can assist in identifying ground engineering risk before major works begin.

Problems affected the new cathedral building from early stages, resulting in the collapse of the new tower in 1220. When one of the largest earthquakes to originate in Britain occurred on 20 February 1247, the structure was significantly impacted, owing partly to the inadequacy of the original foundations and corresponding vulnerability. The resulting effects caused the walls at the west end of the nave to lean outwards as shown in Figure 1.

Descriptions of the earthquake in the annals discussed by Luard (1865) speak of buildings being shaken up to the point of collapse, dishes being thrown off tables and people running out terrified, indicating an estimated earthquake intensity around magnitude 5-6 with a likely epicentre in Wales. As described with latin translations in Lloyd *et al.* (2004), the severity of the earthquake damaged (“corruit”) the cathedral of St Davids and “rupes scissae sunt” (stones were split). While some damage was experienced, the overall design was sufficiently robust such that total collapse did not occur (i.e. ultimate limit state was not reached).

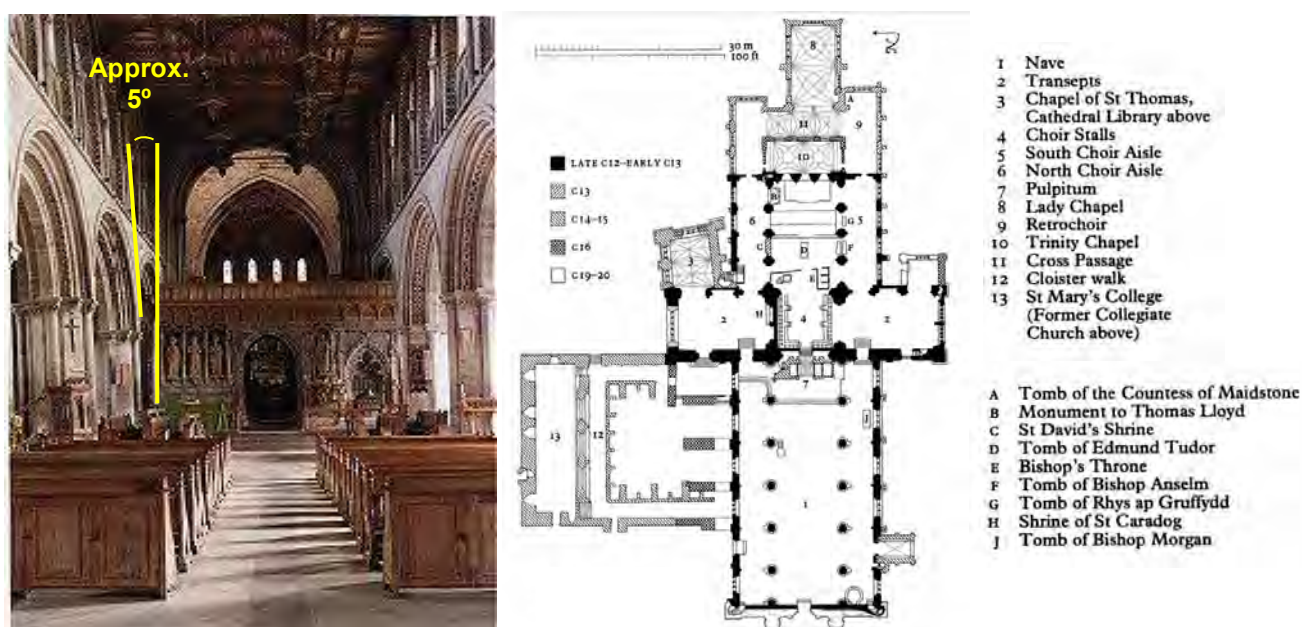


Figure 1: St Davids Cathedral (photo / image source: www.stdavidscathedral.org.uk / Lloyd *et al.*, 2004).

By chance more than design, the cathedral design was sufficiently resilient such that the post-earthquake condition was repairable. This present day notion of designing (intentionally) for an acceptable, repairable damage condition which is intermediate between ultimate and serviceability states under an unusual event has merit and is discussed in later sections.

Following additions and minor reconstruction during the middle-ages (between about 1250 and 1400), a wooden ceiling rather than stone vault was built in the 16th century to reduce loading. This is visible at the top of the photograph in Figure 1. The resulting magnificent pendant ceiling from made from Irish Oak is one of the most spectacular pieces of carpentry in Wales. This simplistic approach of adjusting the design in response to observed performance actually aligns well with the „observational approach“ to construction practice which was first coined by Peck (1969). In essence, this reflective practice cycle can be applied to any project and always starts with a prediction of what you expect to happen. If observations are unexpected then reflection is required to manage risk and refine predictions of future performance (See Figure 2).

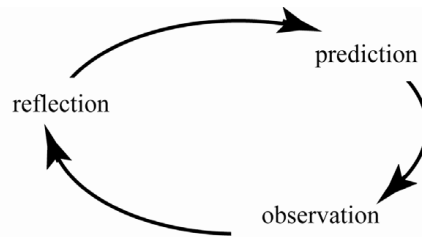


Figure 2: Reflective Practice Cycle.

Following later periods of disrepair and then reconstruction, strengthening works for earthquake affected areas included underpinning which involved an *„audacious feat of engineering of which the architect was justifiably proud“*. Other structural problems affecting the façade also required temporary support, then replacement in the 1880’s (Lloyd *et al.* 2004). After nearly 1,000 years of evolving design and construction which has exhibited some elements of resilient engineering, this structure and centrepiece of celtic culture remains as prominent and beautiful landmark.

Thames Tunnel between Rotherhithe to Wapping, London, England (1825 – 1843 and beyond)

As meticulously documented by Sir Alec Skempton *et al.* (1994), the Thames Tunnel running between Rotherhithe and Wapping in London was built by Sir Marc Brunel between 1825 and 1843 and was the world’s first subaqueous tunnel. Marc Brunel employed his nineteen year old son Isambard as resident engineer on their first job together.

Despite repeated catastrophic inflows from the overlying river into the tunnel workings, the determination and ingenuity of the Brunels” overcame the challenges and developed pioneering technology including the tunnel shield, soil nails, improved investigation techniques and detailed recording systems involving written notes, observations and sketches made during each shift. Now, more than 160 years after it was completed, the oldest tunnel on the present London Underground was recently upgraded to form part of the new £1bn East London Railway Line, prepared for the 2012 Olympics.

The elder Brunel invented and patented a tunnelling shield to deal with the waterlogged Woolwich and Reading Beds and soft (and foul) riverbed sediments beneath the Thames. The shield comprised a cast iron structure (Figure 3) that moved forward as the ground was excavated, with bricklayers constructing the double tunnel behind. Face excavations were undertaken by sequentially removing oak planks one at a time and cutting the soil behind to a depth of four inches (about 100mm). This process required 36 miners, each in his own cell in the shield.

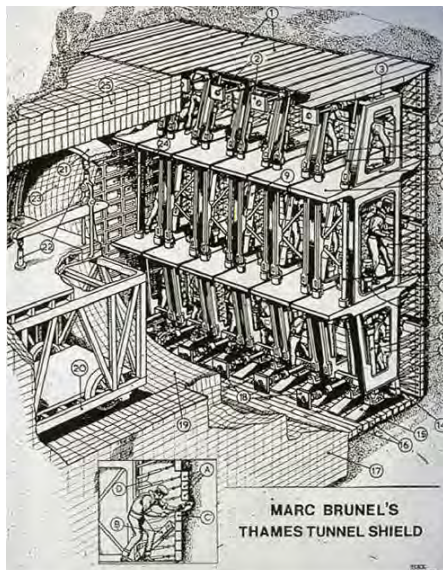


Figure 3: The first ever tunnel shield (photo sourced from www.tunnelsonline.info).

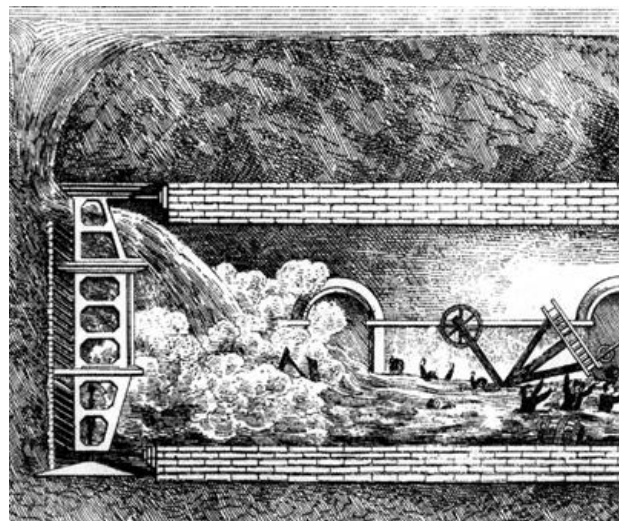


Figure 4: The fatal irruption of January 1828 (photo sourced from www.wiley-vch.e-bookshelf.de).

With a sufficiently thick and stiff clay layer above the tunnel crown and below mixed riverbed sediments this process could be completed without significant ground loss at the face, but where the clay cover was thin (< 6 ft or 2 m), significant water and running sand and silt inflows occurred, causing large settlements and breakdown of the clay ahead

and above the face. In April 1827, flowing spoil from the tunnel face included identifiable riverbed materials apparently including coal, bones, pieces of China (Brindle, 2013) and later a spade interpreted as being dropped by barge workers above (Skempton, 1994). Isambard hired a diving bell to inspect the riverbed which was now covered by so little that on pushing a hollow tube through the mud he could converse with a miner in the tunnel. The intriguing account by Brindle (2013) also relays that Isambard also took his mother down to the riverbed in one diving bell inspection – truly a project of family interest.

In May 1827 about 1,000 tons of soil and an enormous volume of water ran into the workings, requiring plugging of a riverbed sinkhole with 2,500 tons of clay filled bags placed by barges. Fortunately the 100 or so workers managed to escape, however a later inundation in January 1828 resulted in the death of six workers (Figure 4) and Isambard himself was carried unconscious from the tunnel. A seven-year cessation of work followed while new funding arrangements were sought.

These irruptions showed how critical it was to delineate the type and distribution of soil materials at the tunnel crown and face. When this issue became tragically apparent during construction it was realised that early boreholes using a worm drill yielded unsatisfactory information. A second phase of investigations with auger and casing tubes, gave significantly better results, and, along with more detailed riverbed bathymetry, enabled strategic pre-placement of many clay bags at riverbed level to mitigate tunnel face instability. Again, the value of the reflective practice cycle is demonstrated.

On re-starting in 1835, a system of iron bars driven into the face was used to provide temporary support in poor ground. This system of soil nailing was used to facilitate replacement of the old shield and to provide intermittent support during the remaining tunnel drive. Water inflows during construction were typically 100-300 gallons per minute (8-23L/s), and sometimes up to about 1200 gallons per minute (91L/s) in poor ground areas. Ultimately, a total of five uncontrollable river irruptions occurred into the tunnel workings, leading to a modest overall advance rate of about 25m per year during productive work. On completion, the Thames Tunnel was hailed as one of the new wonders of the world, and on its first day of opening 50,000 people walked through the tunnel. Subsequently, a million visits were chalked up in the first 15 weeks and a Royal visit by the year end.

That the project continued and succeeded in the light of such high groundwater inflows, regular uncontrolled irruptions and even fatalities, suggests that the risk appetite then was significantly greater than would be tolerated today. Looking beyond the difficulties, we should also acknowledge the level of perseverance, innovation and personal commitment shown by the Brunel's, which ultimately led to step-change advances in construction techniques that have benefitted society since that time. In the author's view, this more conventional notion of personal resilience, involving mental toughness, versatility, innovation and capacity to deal with challenge or adversity, at an individual leadership level is an essential element of project (and career) success.

19th Century, Port Infrastructure, UK

Early accounts describing port infrastructure challenges in the 19th century are neatly captured by Jarvis (2011). These include discussions held at the UK Institution of Civil Engineers in 1857, decades before the geotechnical discipline was formally recognised. At that time, civil/maritime engineering topics from around the British Empire included deep problematic muds in Southampton Docks, retaining wall movements at Kidderpore Docks (Calcutta, India) and caisson construction using the „*Indian method of well sinking*“.

Jarvis also describes the two worst port construction disaster case histories in UK history. These provide powerful insights into the technical, human and organisational risks which are as relevant today as then. These disasters both occurred in 1909 and together, they triggered some of the first legislative maritime labour, construction and design guidelines which have evolved to guide design and protect construction workers today.

The first example relates to the modernisation of Vittoria Dock (*sic*), Birkenhead, near Liverpool. During demolition work inside a large timber cofferdam, uncontrolled inflow and collapse occurred, killing 14 people. Two primary failure causes were cited, including poor/overstressed design and high groundwater pressure. Significantly, informal post-failure enquiries described the cofferdam as „workmanlike“ suggesting no record of any formal calculation, drawing, or considered construction process, unlike the more diligent documentation of Brunel.

Later that year at Alexandra Dock in Newport, South Wales, another large (18.2m deep) temporary timber retaining structure collapsed with the estimated loss of between 20 and 39 men and widespread damage (See Figure 5).



Figure 5: Pre and Post- cofferdam image, Alexandra Dock, Wales, July 1909 (Photo source: Jarvis, 2011).

The uncertain number of workers affected is a telling indicator of the lack of employer control. While a „general drawing“ was produced by a titled „sub-agent“, the actual temporary support design was effectively undertaken by a poorly educated „ganger“ (four levels of management below the Principal Contractor) who was conveniently and posthumously blamed. Other organisational failings included arbitrary design changes, sporadic/undocumented feedback meetings and a failure to communicate effectively across societal class-based hierarchies.

The Birkenhead failure was seen as a blameless incident, even „*incidental to their calling*“ for dock construction workers of the day. However, the ensuing Newport incident was a tipping point that triggered parliamentary reform including extension of factory worker laws to construction workers. Failure themes in these early case histories, which have been unfortunately repeated since, include:

- Poor planning, organisation and management including inadequate ground investigation;
- Hierarchical roadblocks to communication;
- Inadequate recognition of, or response to, variable site conditions – especially tidal and groundwater effects;
- An absence of systematic recognition, documentation or management of risks or safety in design; and
- A failure to disseminate and act on punishing lessons learnt by others – in the case of Newport, only a few months and Counties apart.

3 EMERGENCE OF DESIGN GUIDANCE

Improvements in the early 19th century came in the form of societal awareness of the need to improve safety and risk management at work, in parallel with the appearance of learned societies and improved workplace legislation. Some key milestones are discussed below, again, focussing mainly on civil/maritime engineering developments in the interests of brevity.

Development of industry associations, design guides and design standards have improved the way that infrastructure works have been specified and engineered. One maritime example, founded in 1852, is the Permanent International Association of Navigation Congresses (PIANC). This is a global organisation providing guidance for sustainable waterborne transport infrastructure for ports and waterways (see www.pianc.org).

Similarly, the industry funded Construction Industry Research Association (www.ciria.org) has produced a number of seminal civil engineering and geotechnical design guides including benchmark manuals on site investigations, seawall design, rock materials and groundwater control.

In the United States, coastal engineering has traditionally been the domain of the military, who for instance, have produced a number of useful guides including The Military Handbook of Seawalls, Bulkheads, and Quaywalls and the well-known Naval Facilities Engineering Command (NAVFAC), Foundations & Earth Structures Design.

Some relevant contemporary maritime design codes include, for example, British Standards BS6349 Maritime Structures (2012-13), Australian Standards AS4997 Guidelines for the Design of Maritime Structures (2005), and AS4678 Earth Retaining Structures (2002). Australian users should note that AS4678 is not intended for use with structures over 15m height (of which many quay walls are), and excludes slopes flatter than 70°, which would exclude many revetment structures.

Over time, international design standards have generally moved away from global safety factoring towards assessment of stability and serviceability performance requirements. This enables more specific and appropriate factoring of

individual actions according to design cases under consideration (i.e. ultimate, serviceability and earthquake). It is worth noting that serviceability performance is a significant risk for port owners/operators due to the commercial drivers around asset availability and maintenance cost. Given the commercial importance of operational reliability, suggested strategies to control this risk are presented in the following sections of this paper.

Lagging behind the evolution of design standards, are formal journals about failure/forensic engineering in which lessons about failures can be documented and shared more widely. The ICE only began publishing the regular Forensic Engineering Journal in 2011, well over than a hundred years following the cited civil engineering failures.

4 LEARNING FROM FAILURE: ENGINEERING RISK MANAGEMENT AND RESILIENCE CONCEPTS

Some key developments in the journey from trial and error based approaches in the early 19th century, to the concepts of safety engineering, established risk management practices and emerging field of Resilience Engineering are discussed below.

4.1 UNDERSTANDING FAILURE MODELS: FROM 'LINEAR' TO 'COMPLEX' SYSTEMS

All engineering projects are delivered through a complex set of designing and constructing processes. Despite improvements in the design process, as documented above, failures still occur due to poor design, poor translation of design intent, or poor implementation (i.e. construction).

Several authors have proposed models that outline conditions leading to failures. Over time there has been a shift from failure models that treat accidents as the outcome of a series of events along a linear pathway, to accidents arising from the interaction of a multitude of events in a complex system. Examples of linear system failure models include „The sequence-of-events model“, „Man-made disaster theory“ and „The latent failure model“ which are discussed further below.

With the emergence of resilience concepts in safety engineering, more complex system models have been proposed such as „Normal accidents theory“, „Control theory“, „High reliability theory“ and „Resilience Engineering“. An extensive discussion of all these theoretical accident models is provided by Hollnagel (2006) and Dekker *et al.* (2008). Only a brief description is provided below with examples and case histories to link them to the themes of this paper.

Figure 6 (from Furuta, 2014) schematically shows the evolution of these failure models over time from linear to complex systems (at top). Notable disaster events are also shown and illustrate how the importance of key factors has changed over time as our collective ability to address the various causal factors has changed (improved?) with time.

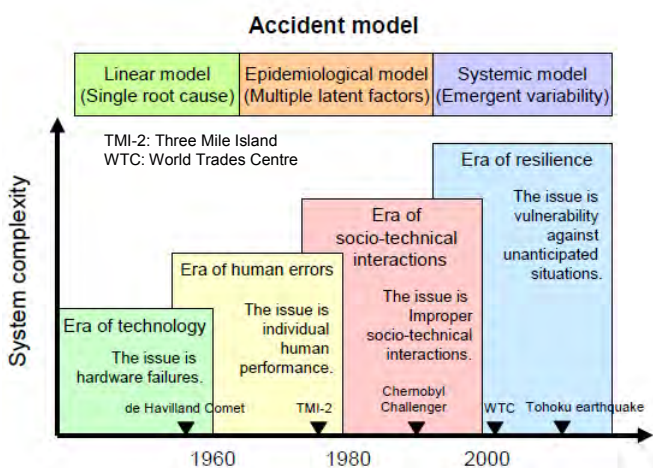


Figure 6: Changing focus of safety systems (Furuta, 2014).

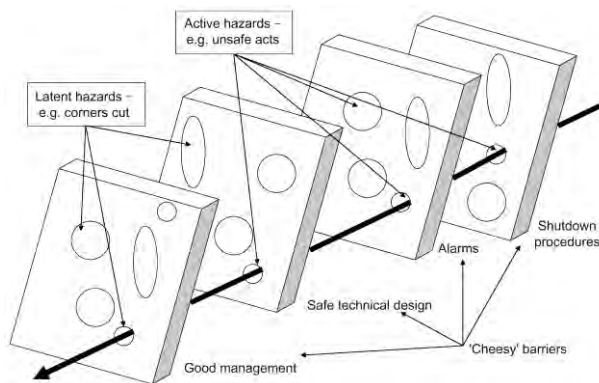


Figure 7: Reasons Swiss Cheese Model - a pathway to failure. (Source: Reason, 1990).

4.1.1 LINEAR FAILURE MODELS

A simple, linear way of conceptualizing how events interact to produce an accident is to imagine them as a sequence, or chain, of events resulting in a mishap. This has also been called the domino model, using the analogy that an accident is the endpoint in a string of falling dominoes (Hollnagel, 2006). This notion also requires a root cause, or trigger at the beginning of the chain that sets everything in motion (the first domino brings down the rest, one by one).

Extended failure models involving multiple parallel or converging sequences forms the basic premise of many risk analysis methods and tools such as fault-tree analysis, probabilistic risk assessment and critical path models. As discussed in Section 9.1, these approaches can be very useful to inform risk management decisions.

Another failure model that emerged from 1960's to the early 1980's includes the notion of barriers - a separation between the source of hazard and the object or activity that needs protection. Using the analogy above, barriers can be seen as blockages between dominoes that prevent the fall of one affecting the next, thereby stopping the chain reaction.

Reason (1990) proposed a „Swiss cheese“ model to explain different barriers that stop failure of a system. As shown on Figure 7, these barriers include a range of measures and good management practices. Each of these barriers can be represented as separate slices of cheese containing holes that will occur during the life of a project. The holes in each barrier move around and appear and disappear as issues are identified and resolved. It is when holes line up through all the individual slices that a path to failure is completed.

The idea of separating sources of hazard from objects or processes that must be protected by a linear series of barriers is also sometimes thought of as a way of reducing hazard „energy“ as it works through system. For example, road safety strategies also aim to reduce the amount of hazard „energy“ (i.e. kinetic energy) by controlling release of harmful energy by introducing „barriers“ such as speed limits, salting of icy roads, energy absorbing wire-rope median barriers, and passenger airbags (Rosness *et al.*, 2004).

Within the same family of linear systems thinking, the „latent failure model“, also termed the „incubating accidents“ model by Turner and Pidgeon (1997), involves the concept whereby a build-up of adverse factors creates the pre-condition for failure. A useful analogy describing the onset of failure in such a system is that of an inflating balloon. Imagining pressure as representing the likelihood of failure, then as a balloon grows in size, so does failure potential. Adverse events contribute to an accumulation of pressure and hence failure probability. The size of the balloon (and hence failure probability) can be reduced by letting air out. For example, this could be due to effects of management decisions that remove some of the risk.

If the pressure of events builds up until the balloon is very stretched, then only a small trigger event, such as a needle or lighted match is needed to burst the pressure pent up in the system. The trigger is often mislabelled as the cause of the accident, as the over-stretched balloon is an accident waiting to happen. Team leaders should look for evidence of the building pressure in the balloon – to spot the accident waiting to happen – and diagnose the necessary actions to reduce risk.



Figure 8: Post-failure photo of Nicoll Highway Collapse.



Figure 9: Landslide at Aberfan in 1966 (photo sourced from www.nuff.ox.ac.uk).

A classic example of a geotechnical failure viewed using this analogy is the Nicoll Highway disaster in Singapore which occurred in 2004 when a 30m deep section of cut and cover tunnel collapsed killing four and injuring three (Figure 8). The original design misinterpreted the local geology (missing a buried channel of alluvium) and overestimated the soil shear strength in its analysis. The pressure in the balloon was hence high from the outset. This was compounded by an under-design of the strut-waler support system connections by 50% where splays were omitted.

Signs of trouble such as buckling of plate stiffeners and accelerating ground movements were not appropriately recognised or escalated. At this point, the catalogue of errors and internal communication failures was an accident waiting to happen. The trigger to the „balloon burst“ and rapid collapse was initiated by forced sway failure in lower struts which was an inevitable consequence of the design errors. A recap of learning's from the 1909 Newport dock

disaster in Section 2, above, reveals remarkably similar people and process failings similar to Nicoll Highway over 100 years later. Even the appearance of the end result is hauntingly similar (compare Figures 5 and 8).

In Turner's 1976 study of the 1966 Aberfan coal stockpile disaster in Wales (Figure 9), the geotechnical factors behind failure were caused by elevated pore pressures in the accumulated rock and shale waste dump, which rapidly deteriorated into a fluidised flow-slide on 21 October 1966, killing 116 children and 28 adults. On closer inspection, Turner found that the failure exhibited „incubating“ type characteristics having wider causal factors which were common to other disasters including:

- Rigidities in institutional beliefs
- Distracting decoy phenomena, neglect of outside complaints
- Multiple information-handling difficulties
- Exacerbation of the hazards by strangers
- Failure to comply with regulations
- A tendency to minimize emergent danger.

This work showed that disasters were not necessarily “created overnight” as the pre-failure conditions had been incubating for periods of up to years. A second observation was that the Aberfan failure and other man-made disasters he examined were not caused by a single factor but by a mix of disaster triggering events which had accumulated over time.

This was an important step towards linking multiple causal factors in more complex interrelationships and brings us to the emergence of Resilience Engineering concepts which is a more recent systems approach to understanding safety and risk. This approach brings with it the ability to build-in systems and controls to absorb change, error and disturbance in complex systems such as engineering projects without breaking down, without catastrophic failure. Truly resilient systems go beyond these protection measures towards enhancing the capacity and performance of infrastructure.

4.1.2 COMPLEX FAILURE SYSTEMS – TOWARDS RESILIENCE ENGINEERING

As discussed in the previous section, implementation of combined operational and engineering measures (or barriers) make many systems or projects relatively safe from pre-determined single point failures; that is, they are protected against particular adverse design events or failings of people, products of processes which would otherwise directly lead to bad outcomes.

Resilience Engineering departs from conventional safety risk management approaches based on componential approaches (e.g. elimination, removal, near-miss analysis, calculation of failure probabilities). Instead, Resilience Engineering looks for ways to enhance the ability of systems, organisations or projects, to monitor and revise risk models, to create processes that are robust yet flexible, and to use resources proactively in the face of disruptions or ongoing production and economic pressures.

Here, the word „system“ can be read as „project“, and in the context of this paper, perhaps more specifically „infrastructure project“. Dekker (2008) identifies that a system's resilience includes properties such as:

- **buffering capacity:** knowing the size or kinds of disruptions the system can absorb or adapt to without a fundamental breakdown in performance or in the system's structure;
- **flexibility:** the system's ability to restructure itself in response to external changes or pressures;
- **margin:** how closely the system is currently operating relative to one or another kind of performance boundary;
- **tolerance:** the brittleness of a system and whether it gracefully degrades as stress/pressure increase, or collapses quickly when pressure exceeds adaptive capacity.

These properties can be considered alongside adverse disturbing forces such as tensions created by the need to carry out work under time pressure or other resource constraints, resulting in a „resilience triangle“ (Rasmussen, 1997) with boundaries defined by functionally acceptable performance, economy and safety. In cases where crossing the boundary is irreversible, an error or an accident may occur. The dynamic interplay between these different constraints and objectives is illustrated in Figure 10.

This illustrates how multiple pressures act to move the operating point of the organization or project in different directions. For example, management pressures towards efficiency can drive any given risk position towards unacceptable safety or workload outcomes. Conversely a desire to take the path of least effort (i.e. taking short-cuts or laziness) can compromise safety or efficiency, or excessive focus on robustness can reduce efficiency and risk economic failure.

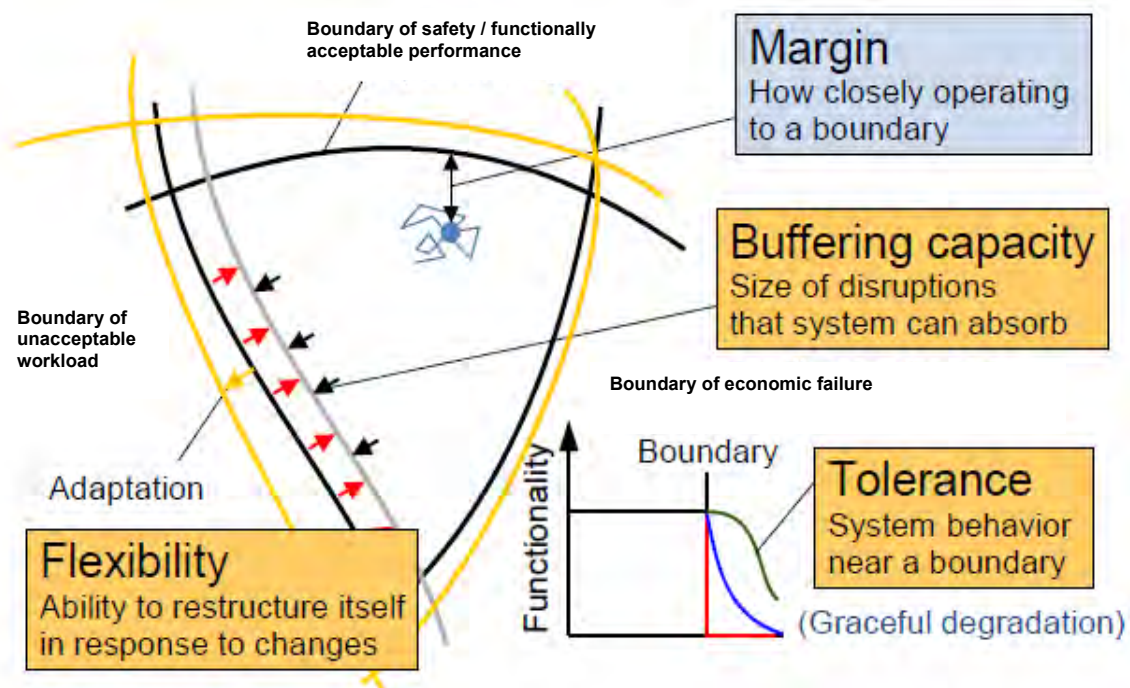


Figure 10: The resilience triangle bounded by constraints: safety, workload and economics (adapted from Furuta, 2014).

The case of the space shuttle Columbia disaster in 2003 is extensively used by Dekker (2006) to explore patterns that have helped shape the ideas behind Resilience Engineering. Some of these causal factors have their basis in the earlier models described by Turner previously, including:

- Drift toward failure as defences erode in the face of production pressure.
- An organization that takes past success as a reason for confidence instead of investing in anticipating the changing potential for failure.
- Fragmented distributed problem-solving process that clouds the big picture.
- Failure to revise assessments as new evidence accumulates.
- Breakdowns at the boundaries of organizational units that impede communication and coordination.

The fourth point affecting the Columbia mission, involves the failure to recognise and act on new evidence resonates strongly with aforementioned civil engineering failures – especially the Nicoll Highway, discussed above. The key here is to identify and have the courage to revise once-plausible designs as new evidence comes in. Revising assessments successfully requires getting a “fresh” view, often by bringing in people new to the situation; through interactions across diverse groups with diverse knowledge and tools; and or through new visualizations which capture the big picture and reorganize data into different perspectives.

Resilience Engineering therefore requires practices to provide decision support for balancing production and safety trade-offs, and creation of feedback loops that enhance the organization’s ability to monitor and revise risk models and protect safety. This can include monitoring for effective cross-checks when risky decisions are made or understanding the brittleness of a design by undertaking sensitivity studies (discussed further in Section 7).

In an infrastructure context, project leaders need sufficient awareness to know when to relax the pressure on throughput and efficiency and make trade-off decisions to sacrifice production over risk – especially when approaching safety boundary conditions. Ironically, it is at the very times of higher pressure and focus on acute goals that resilience behaviour is needed to keep these production/safety trade-offs in balance.

When operating under production and efficiency pressures, evidence of increased risk on safety may be missed or discounted. As a result, organizations act in ways that are riskier than they realize or want, until an accident or failure occurs. This is one of the factors that create the drift toward failure signature in complex system breakdowns. For example, the need to make aerospace operations reliable also makes them very complex, resulting in layers of obscuring processes and procedures which can themselves present unintended hazards.

Since the application of linear systems approaches to safety engineering, researchers such as Perrow (1984) have identified that adding many barriers and redundancy can paradoxically, add complexity and reduce clarity so that when

even small things start going wrong it becomes very difficult to see the problem and get off an accelerating pathway to failure. Indeed the case of an aircraft crash involving a Boeing 737 leaving Cyprus in 2005 reported by Dekker (2008) demonstrates that even highly prescriptive barrier-based and codified systems can result temporary inability to cope effectively with complexity, in this case due to misunderstandings caused by poor language skills. In these cases training of Resilience Engineering principles may help such as having the courage to speak up, identifying the consequences of ambiguous/hazardous/decoy information, understanding the „brittleness“ of safety situations and understanding the trade-offs between commercial pressure and accident risk.

In the words of Adjunct Professor Tim Sullivan (experienced consultant appointed as Mine Warden to the 2007 Yallourn Coal mine collapse), the people responsible for maintaining safety can sometimes „fail to hear the sound of the bus coming“. With this in mind a classic example of incrementally increasing safety risk is captured by the following case history in Petroski (2000), reproduced from Dekker (2008). This case is reproduced in full below due to the exceptional clarity of these concepts conveyed:

CASE: TEXAS A&M UNIVERSITY BONFIRE (PETROSKI, 2000)

The Texas A&M University bonfire tragedy is a case in point. The accident revealed a system that was profoundly out of control and that had, over a long period, marched towards disaster. On November 18, 1999, a multi-story stack of logs that was to be burned in a traditional football bonfire collapsed while being built by students at the Texas A&M University [Figure 11]. Twelve students working on the structure were crushed to death as the structure collapsed. Twenty-seven others were injured. It was the worst such disaster at a college campus in the United States and was devastating within the tight knit community that prided itself on its engineering college. An independent commission was established to investigate the causes of the collapse. Extensive and expensive engineering studies were conducted that showed that the collapse was the result of specific aspects of the structural design of the bonfire. It revealed that the collapse happened because the bonfire had evolved from being a conventional bonfire into a large scale construction project. That project had never been competently designed or analyzed and was largely carried out by unsupervised amateurs.

The bonfire was a Texas A&M football tradition that extended over many years. It began in 1928 as a haphazard collection of wooden palettes. It grew gradually, increasing in scale and complexity each year until the 1990's when it required a crane to erect. In 1994 a partial collapse occurred but was attributed to shifting ground underneath the structure rather than structural failure per se.

The catastrophe five years later overwhelmed the medical facilities of the area. The response to the failure made it clear that no one imagined that this sort of disaster was possible, let al. one likely. In hindsight, it seems incredible that this should be the case. Even here hindsight misleads us into believing that the inevitability of this particular sort accident should have been apparent. It was not at all obvious before the fact. The relative lack of failure over many years produced a sense that failure was unlikely, even though the growing structure over the years was taking the system in that direction. Each increment in complexity and scale was too small to signal that the system was becoming dangerous in new ways. The bonfires of the late 1990's reached new heights without anyone understanding what those heights meant. The inability to recognize that the system was unsafe was a property of the system itself, a property essential to the development of the accident situation.



Figure 11: Texas A&M University Bonfire (Source: ww3.hdnux.com/photos, www.ruhr-uni-bochum.de).

Against the backdrop of success, warning signals like the partial collapse could be discounted. The partial collapse was treated as an incident. It was not large enough to garner the sort of attention needed for the kind of detailed examination that would show how dangerous these new bonfires were. Only a truly catastrophic failure was enough to produce a new look at what the bonfire had become. The group managing the bonfire had marched into tragedy with their eyes open but unable to interpret what they were seeing.

This illustrative example fits very closely with the incubating failure model in which almost all of the causal factors identified by Turner (1976) are satisfied. Reflecting on this with the benefit of hindsight, it is worth asking ourselves if the same pathway would have been followed, had the parties responsible for the bonfire displayed the following characteristics of a resilient organisation:

- **Preparedness/anticipation** - is the organization proactive in picking up on evidence of developing problems versus only reacting after problems become significant?
- **Opacity/observability** - does the organization monitor safety boundaries and recognize how close it is to „the edge“ in terms of degraded defences and barriers? How widely are safety concerns distributed throughout the organization?
- **Flexibility/stiffness (brittleness)** – is the organization or processes nimble enough to adapt to change, disruptions, and opportunities? How quickly could something go wrong and go out of control?

Resilience is not necessarily about reducing negatives (incident recording, rule violations, etc.), it's about identifying and then enhancing the positive capabilities of people and organizations that allow them to adapt effectively and safely under pressure. For example, systems which encourage learnings, feedback and open communication about system failures should be encouraged and rewarded. The degree to which the reporting of safety concerns and problems is truly open and encouraged provides another significant source of resilience within the organization. Assessing the organization's response to incidents indicates if there is a learning culture or a culture of denial.

Recognising that there are infinite permutations of complexity involved in large scale engineering projects, the author considers it helpful, as a starting point, to focus on the three key risk management categories which contribute towards failure or shortcoming in performance. These are the „3Ps“ being people, processes and products. These factors reinforce the concept that in addition to technical issues, engineers have to deal with a wide range of human and organisational issues including social, political and legal systems.

5 ROLE OF PEOPLE

Paraphrasing the first axiom of Worden *et al.* (1976), „*All social systems have inherent flaws or defects*“. This can often lead to human factors in failures. Organisational and cultural situations may exacerbate the potential for failure and unfortunately these may be difficult for those close to or within teams or certain cultural environments to identify. The importance of multiple human or organisational factors in failure is complex because failures may not be solely linked to mistakes by individuals. Rather, they may also be impacted by organisational and/or cultural context.

Individual human frailties lie behind many failures. Although many people related risks are mitigated through safety rules, prescriptive procedures and management processes, people don't always do what they are supposed to do. This can arise through apathy, malice, laziness, stupidity, confusion or a whole range of other rational and irrational reasons.

This uncertain aspect of human behaviour screams out „unreliability alert!“, an erratic, unpredictable form of variability that we should aim to engineer out of systems through more automation, better education or indoctrination in safety, stricter procedures, and/or (in fact, ideally), tighter monitoring of workplace behaviour. As history shows, “human error” is often the product of factors that lie deeper inside the operation and organization. To help mitigate this embedded people risk, review processes involving people from outside an organisation or team may be of great benefit as they may be able to assist in the identification of risk unseen by people buried in detailed design (think: the master cathedral builder who knows when things „look wrong“).

In design and construction applications, such people may be appointed on projects as internal reviewers, or as independent verifiers. Imagine the scenario of a Project Director / Reviewer on a large scale infrastructure project who has to come to the aid of a struggling design team to address a critical, high pressure issue. By involving themselves in design they are no longer able to offer the critical independent insight and review necessary to maintain an awareness of emerging risks. In this sense, Isambard Brunel may have been better off away from the tunnel face where he could make objective assessments of site behaviours and project risk.

Generally issues may be most easily addressed where all parties involved in a project have agreed to share risk and reward. Alliance contracts, for example, help to focus people on flaws and risks in a collaborative way. However,

Alliance forms of contract delivery are becoming less common due to the overall perception of reduced client value. Alternatives such as design-and-construct, or design/construct only delivery models involve multiple corporate interfaces which can inhibit collaboration between parties and over-prioritise commercial drivers. As an industry seeking a pathway towards Resilience Engineering, we, as individuals and industry societies, should openly discuss with and encourage project sponsors to engage with collaborative delivery models where parties are incentivised across a range of non-commercial key performance indicators.

Also important is the role of leadership in the prevention of failure. Factors include leadership „authority“ and „style“ and culture setting. For instance, a culture of blind „obedience to authority“ was partly to blame for the Newport disaster. Ultimately, though the underlying philosophy of Resilience Engineering, is not to focus on human error at all, but instead focuses on the ability of the organisation, system or project to overcome people risk.

6 ROLE OF PRODUCTS

Product failures in the sense of conventional forensic engineering commonly relates to the unplanned behaviour of manufactured materials or members which then trigger collapse.

Examples of poor „product“ design include Ronan Point apartment building collapse in London in 1967 which occurred due to a localised explosion of a burst gas pipe. The resulting cascading failure of multiple floors highlighted poor design of the prefabricated connections. This concept was also identified as important in the World Trade Centre in 2001, and prompted checking of the capacity of structures against total collapse mechanisms due to explosions.

Arguably, these types of manufactured product failures are an extension of process or people failures, either due to poor design, specification or quality control, or because of inadequate structural redundancy. In the context of this paper, geotechnical failures such as excessive movement or collapse of a structure could be viewed either as either a „product“ failure of the ground as a natural material with assumed or interpreted properties; or as a „process“ failure of the design to account for the intrinsic variability and uncertainty of the ground and its interpreted properties. For the purpose of this discussion, geotechnical uncertainty is captured and discussed below as a „process“, risk rather than a „product“ risk.

7 ROLE OF PROCESSES

Unlike other engineering disciplines in which the strength of materials may be well understood, controlled and quality tested prior to and during construction, the ground is a variable material. Conventionally a limited number of investigation locations, such as boreholes, will be undertaken which cover only a small proportion of the overall volume of ground occupied by any project. From this information geotechnical engineers develop an inferred model of the geological conditions and corresponding material properties.

The investigation, design, construction and monitoring process is a well-developed routine applicable to most port infrastructure works, but which has many pitfalls for the unwary. Good design will also consider the robustness or efficient forms of redundancy in a design. This risk assessment process is important, even where design and construction risks have considered and addressed all reasonable standards. Most designers are conscious of providing some additional safety margin or redundancy for critical elements of design which prevent collapse type failure mechanisms. This must be balanced against the cost of such comfort, but it can make a pivotal difference in cases where unforeseen loads apply to structures. Examples of poor design process include failures of port structures in Malaga and Barcelona (Del Campo *et al.*, 2011). These caisson structures were postulated to have collapsed due to:

- Lack of information on the in-situ ground conditions below the structures (a theme common to many of the cases in this paper);
- The foundation for the structures were insufficient to transfer applied loads;
- Structural and filling operations being completed by different contractors;
- The nature of reclamation fill was poorly understood and it was placed very quickly to maximise production;
- The sequence of filling caused a “lake” inland of the structures which then unintentionally acted as dams; and
- The tidal and wave variability was not considered during the design.

In both of these projects water had an impact on the failures, both in terms of hydrostatic pressures on a structure and excess pore pressures generated by rapid placement of fill. More active risk and interface management processes and review between designer and contractor would have reduced risk in this situation.

Another significant opportunity to mismanage process risk involves numerical modelling. In recent times the use of sophisticated geotechnical models to assess behaviour of the ground has become routine. However, failures have occurred due to misinformed or incorrect use of complex models, such as the Nicoll Highway Collapse. When considering the results from any model it is useful to consider the anonymous adage that “*All models are wrong - but*

some are more useful than others". Respected Imperial College Professor David Potts (2003) also discussed potential difficulties associated with numerical modelling as follows:

- There is no standard strategy for implementation of nonlinear models;
- Some constitutive models seem to be unable to give reasonable predictions;
- Even for apparently simple problems, the results of numerical modelling can be very dependent on the decisions made by the user;
- Useful numerical modelling requires skilled operators who have a detailed understanding of; soil mechanics, the underpinning theory for the numerical algorithms, limitations of constitutive models and are knowledgeable about the software that is being used.

This is not to say that use of numerical modelling is not an appropriate tool. Rather, reviews should always be completed by experienced practitioners and appropriate benchmarking or independent checks undertaken. Key questions to ask about numerical models include:

- Are we getting the answers that we think we are getting?
- Are we getting the answers that we need?
- Can we justify/understand the results using back of the envelope calculations?

Going beyond deterministic design approaches, reliability-based design (RBD) is a design approach involves evaluation of key input variable uncertainties, enabling the designer to convey to stakeholders the confidence level associated with design outcomes such as stability, settlement, etc. Using RBD is not possible with a working stress design (WSD) approach but rather limit state design. This can require development of numerous sets of input parameters and associated partial factors, which requires greater work on the part of the designer. However, this approach does lend itself to appropriate factoring of a greater variety of load cases and scenarios such as groundwater fluctuation in response to flooding events and earthquakes, both of which are important in geotechnical engineering terms.

Problems such as time-dependent settlement can be framed usefully in probabilistic terms and can provide a rational basis for adopting risk positions on key issues having significant commercial or safety implications. The extra time and effort involved with undertaking reliability based design may be justified where risks are significant. Reliability analyses such as those outlined by Duncan (2000) can be done with relatively little additional effort and provide a logical framework for choosing FoS values that are appropriate for the degree of uncertainty and the consequences of failure.

These methods provide a measure of confidence in the spread of outcomes, noting that probability of failure should not be viewed as a replacement for factor of safety, but as a supplement. Indeed calculation of both factor of safety (FoS) and failure probability is better than computing either one alone. Although neither FoS nor failure probability can be assessed with high precision, both have value and each enhances the value of the other. Hence the use of such sensitivity analyse and RBD approaches aligns well with the notion of Resilience Engineering which requires an understanding of the brittleness of a system (or design) so that appropriate controls can be applied to stay within the optimum areas within the „resilience triangle“ (Figure 10).

8 TOMORROW'S WORLD

This section looks at some global and local societal, economic and environmental trends and considers how what risks and opportunities these present to geotechnical and infrastructure engineering. With this in mind, the final sections of this paper look at how these trends may act on geotechnical and engineering practitioners, and how these tensions may be dealt with by adopting Resilient Engineering principles.

8.1 GLOBAL MEGATRENDS

Significant shifts in environmental, economic and social conditions that will play out over the coming decades may be termed a „megatrend“. A recent CSIRO study (Hajkowicz, 2012), identified six interrelated megatrends affecting the world and Australia over an indicative time frame of 20 years. These are:

- **Competition for natural resources.** The earth has limited supplies of natural mineral, energy, water and food resources essential for human survival and maintaining lifestyles. In Australia, the population is expected to reach 34m by 2035 (ABS)
- **Biodiversity at risk.** Many of the world's natural habitats, plant species and animal species are in decline or at risk of extinction.
- **Global economic shifts.** Coming decades will see the world economy shift from west to east and north to south (Figure 12).

- **Ageing population.** Australia and many other countries that make up the Organisation for Economic Cooperation and Development (OECD) have an ageing population.
- **Increasing connectivity.** This megatrend recognises increased connectivity where individuals, communities, governments and businesses are immersed into the virtual world to a much greater extent than ever before.
- **Higher expectations.** This is a consumer, societal, demographic and cultural megatrend. There is a rising demand for experiences over products and the importance of social relationships is increasing.

For the purposes of this paper, the Author has added one other trend:

- **Demand for Transport Infrastructure:** In Australia, travel demand will increase by 60% by 2035 (DoIT) and congestion will cost AU\$20bn p.a. by 2020.

How are these megatrends and local changes linked to the notion of resilient engineering? Table 1 below, explores some of these issues and what they could mean to engineers in Australia.

Table 1: Megatrends: Challenges and Opportunities for Engineers

<i>Megatrend</i>	<i>Engineering Risk or Challenge</i>	<i>Engineering Opportunity</i>
Competition for natural resources	<ul style="list-style-type: none"> • Increasing cost of raw materials to society. • Responsible and ethical development of resources in developing countries with unrest / political constraints (i.e. ebola, ISIL) 	<ul style="list-style-type: none"> • Investment / demand for improved exploration, extraction, processing and generation of energy from conventional fuels. • Investment in new technologies for alternative materials, fuels and energy sources.
Biodiversity at risk	<ul style="list-style-type: none"> • Challenge to promote genuinely sustainable infrastructure development. • Associated effects of climate change (See Section 8.2) 	<ul style="list-style-type: none"> • Opportunity to re-develop brownfield sites thereby preserving natural habitat. • Greater use of recycled materials. • Factoring in potential effects of climate change to improve robustness and design life (See Section 9).
Global Economic Shifts	<ul style="list-style-type: none"> • Reducing engineering resilience due to rapid economic development and engineer skills shortages. Example: major infrastructure failures in South Korea in 1990's. 	<ul style="list-style-type: none"> • Greater harmonisation and collaboration between international consultants and contractors creates shared knowledge and experience. • Increased demand in containerised shipping and associated port facilities. Berth upgrades also required to accommodate larger vessels due to widening of Panama Canal.
Ageing Population	<ul style="list-style-type: none"> • Reducing pool of taxation and funding for public projects. 	<ul style="list-style-type: none"> • The ageing population and engineering practitioners are an asset who could be engaged as mentors and to disseminate knowledge.
Increased connectivity	<ul style="list-style-type: none"> • Potential over-reliance / dependency on IT / IM systems to perform safety critical tasks. 	<ul style="list-style-type: none"> • Telecommuting / teleconferencing and associated offset in transport demand and resources use. • Adoption of BIM and associated improved efficiencies, reduced re-work and improved infrastructure versatility (See Section 9.2)
Great expectations	<ul style="list-style-type: none"> • Society expectations of high levels of transport user satisfaction (journey times reliability, comfort levels) requiring increasing levels of engineering. 	<ul style="list-style-type: none"> • Increasing disposable incomes and access to motor and air travel driving investment in transport infrastructure.
Demand for Transport Infrastructure	<ul style="list-style-type: none"> • Limitations on Infrastructure development due to 3-4 year Political & Budgetary cycles. • Widening infrastructure gap (Demand Vs expenditure, Figure 13). • Continuing societal demand for reducing transport fatality rates. 	<ul style="list-style-type: none"> • Requirements for other sources of revenue (Private Public Partnerships (PPPs); capture community funds such as superannuation investments; develop new user-based sources). • Innovation to find greater efficiency and durability in design and construction (See example below). • Improvements in transport safety engineering and automated transport systems. Example: Rio Tinto's driverless trucks have now moved more than 100 million tonnes of earth in the Pilbara.

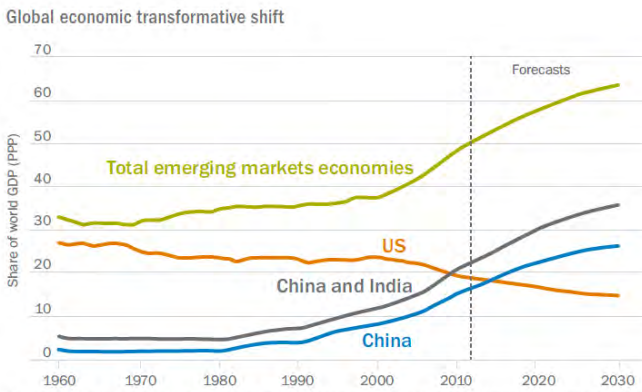


Figure 12: Global Transformative Shift (Source: The Conference Board Economy Database, Maddison (2010).

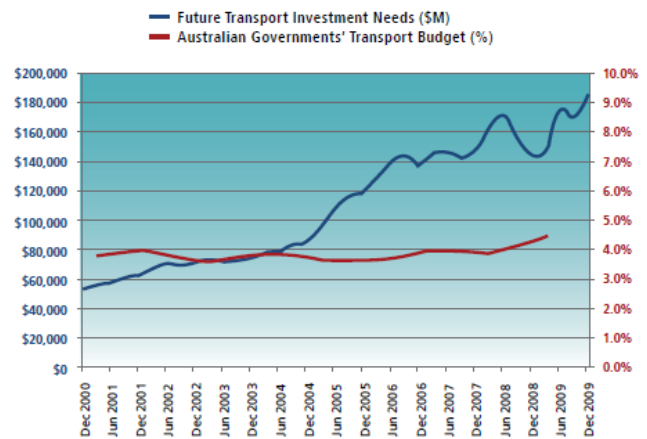


Figure 13: Future Australian Transport Needs (Source: National Transport Commission, Annual Reports).

An over-arching megatrend reaching across those identified above relates to the effects of climate change, the specifics of which are discussed in the Section 8.2, below. This is possibly the greatest single challenge affecting the engineering community (and community at-large) and so an example of the actual and projected challenges associated with extreme weather events and rising sea levels are explored using a real-world example in Section 9.

8.2 CLIMATE CHANGE

Into the future, climate change presents an emerging challenge to performance durability of coastal structures. Research presented in Figures 14 and 15, below suggest that sea level has risen by about 200mm over the last 130 years and may rise between about 200mm and 800mm by 2100. Design standards now incorporate a requirement to consider these impacts in design.

The Intergovernmental Panel on Climate Change (IPCC) has found that warming of the climate system is unequivocal and that anthropogenic greenhouse gases are very likely responsible. Predictive work indicates that this warming will accelerate into the future due to continued anthropogenic greenhouse gas emissions and this will influence sea level. While there is uncertainty about the rate and amount of future rise, there is a high degree of confidence that sea level will continue to rise, and possibly accelerate, over the next century and beyond, through a combination of mechanisms including thermal expansion of the ocean, melting of glaciers and ice caps and changes in terrestrial storage.

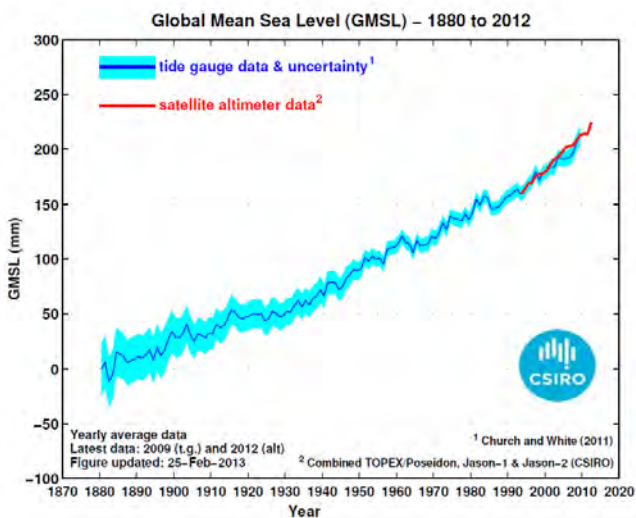


Figure 14: Past Sea Level Rise (Source: IPCC 2007 Fourth Assessment Report).

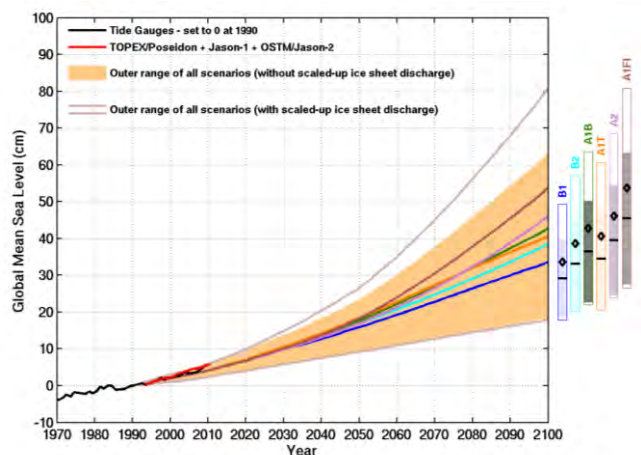


Figure 15: Future Sea Level Rise (Source: IPCC 2007 Fourth Assessment Report).

The three scenarios developed by CSIRO for sea level rise between 2030-2100 (relative to 1990) are presented in Table 2, below.

events because it was designed for a lesser, more frequently occurring design load, corresponding to an event having a lower return period. However, on any given day, events equivalent to, or worse than, the designed-for event can happen. As discussed below, the lower the ULS design event severity, the higher the probability that the asset will be exposed to the ULS event, even taking into consideration the reduced design life. In the case of the Philippines port example, an event exceeding the ULS capacity occurred during the life of the structure.

To illustrate the design challenge, it is worth exploring the relationship between typhoon recurrence, design life and how future sea level rises might affect the capacity of existing infrastructure to absorb climatic changes such as sea level rise. Based on published data estimating the return period of typhoon recurrence (Table 3), it is possible to represent this graphically as Shown on Figure 18. In accepting reduced design life, the consequences of losing key assets (such as wharf structures) should be considered and cost-benefit studies for various return periods for various return periods undertaken, remembering that the minimum capital cost may produce the maximum unreliability.

In 2006, a „super typhoon“ described as „the worst for many years“ affected the Philippines port area. Design wind speed for project was 200kmh, and based on report by Guard et al. (1999) this corresponds to a recurrence interval of about 1 in 30 years. It is worth noting that the definition of design speed as recommended by the World Meteorological Organization (WMO) and used by most weather agencies, is the average speed measured over a 10-minute period at a height of 10 m above ground.

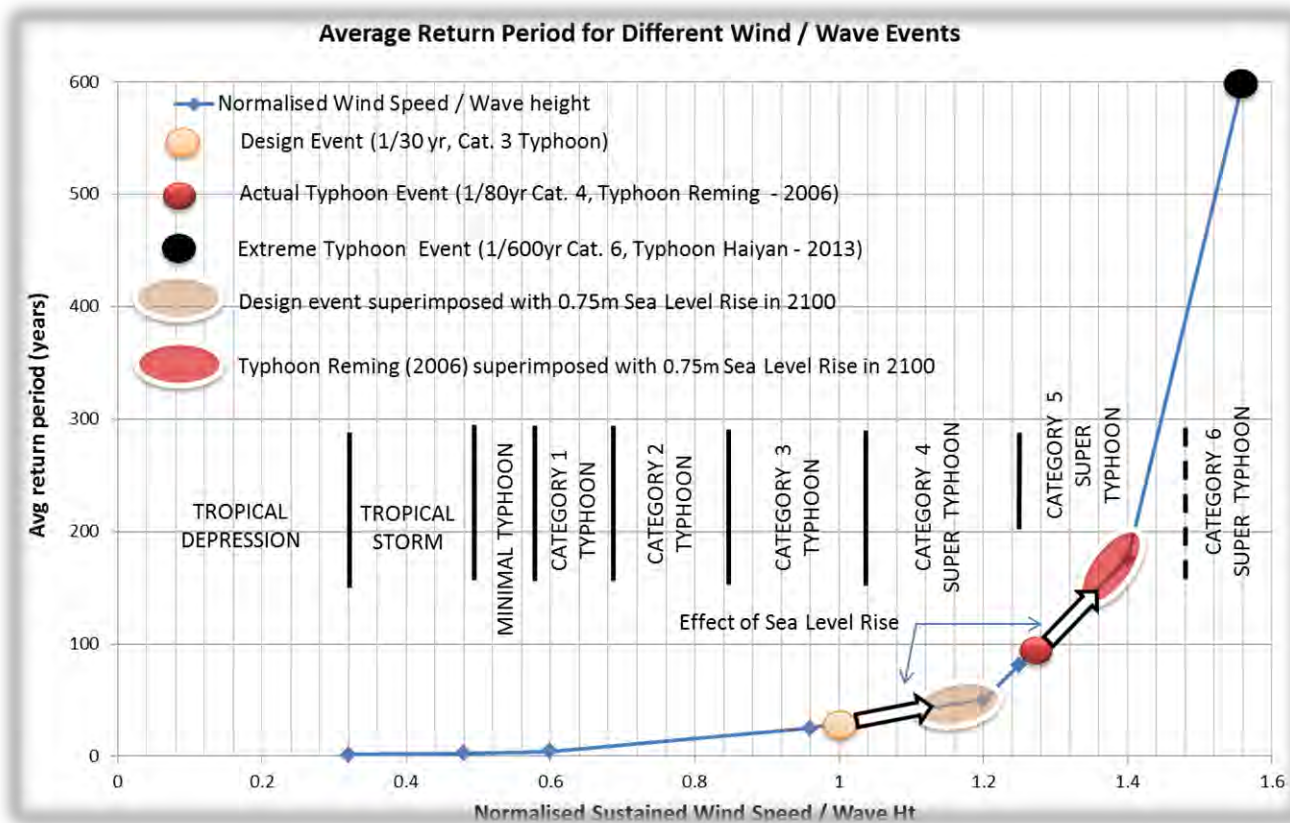


Figure 18: Return Periods for Various Wind Events.

Damage to port infrastructure may be due to combinations of wind and waves, hence the two conditions are often considered separately in design of any particular asset. Considering cranes and revetments, for instance, the capacity of these structures is governed by wind and waves, respectively.

Considering firstly sustained wind speed as a governing cause of damage for the case history in question, it can be seen that the 200 km/hr sustained wind speed design condition approximates to a roughly 1 in 30 year event, based on published data (Guard et al., 1999), as shown graphically on Figure 18. The documented „Super Typhoon“ Reming which hit the port in 2006 reached sustained wind speeds of 250 km/hr, which, by interpolation corresponds to an event having a return interval of about 80 years. For comparison, the Super Typhoon Haiyan, known in the Philippines as Typhoon Yolanda in 2013 is also shown in Figure 18. Haiyan was the strongest storm ever recorded at landfall, and unofficially the strongest typhoon ever recorded in terms of wind speed with maximum ten-minute sustained winds at

275 km/h (170 mph), unfortunately killing more than 6,000 people in the Philippines alone. Based on data published by Guard et al. (1999), the estimated return period for this event is 1 in 600 years.

The likelihood of any particular asset experiencing these events in any given period can be assessed using Figure 19, which shows likelihood of events occurring over a range of typical design life intervals. For example, the probability of occurrence of a rare (or severe) event such as Haiyan with a 1/600 year return period would be only 0.05 (5%) over a 100 year design life.

For the case history in question, the design sustained wind speed adopted was 200km/h (1/30 year return period) and this was selected on the basis that the design life was relatively short at 7 years. This puts the probability of occurrence at about 0.21 (21%) in the seven year design life as shown in Figure 2.

When the „Super Typhoon“ Reming occurred near the end of construction in 2006 (red dot in Figure 19), this rarer 250km/h wind speed event (1/80 year return period) had only a 8% chance of occurring during the 7 year design life, however, it underlines the principle that adverse events can occur at any time during the design life. The likelihood of the 2013 Haiyan type event occurring would only be about 1%, however, interestingly this also occurred within the 7 year design life of the development (constructed in 2006).

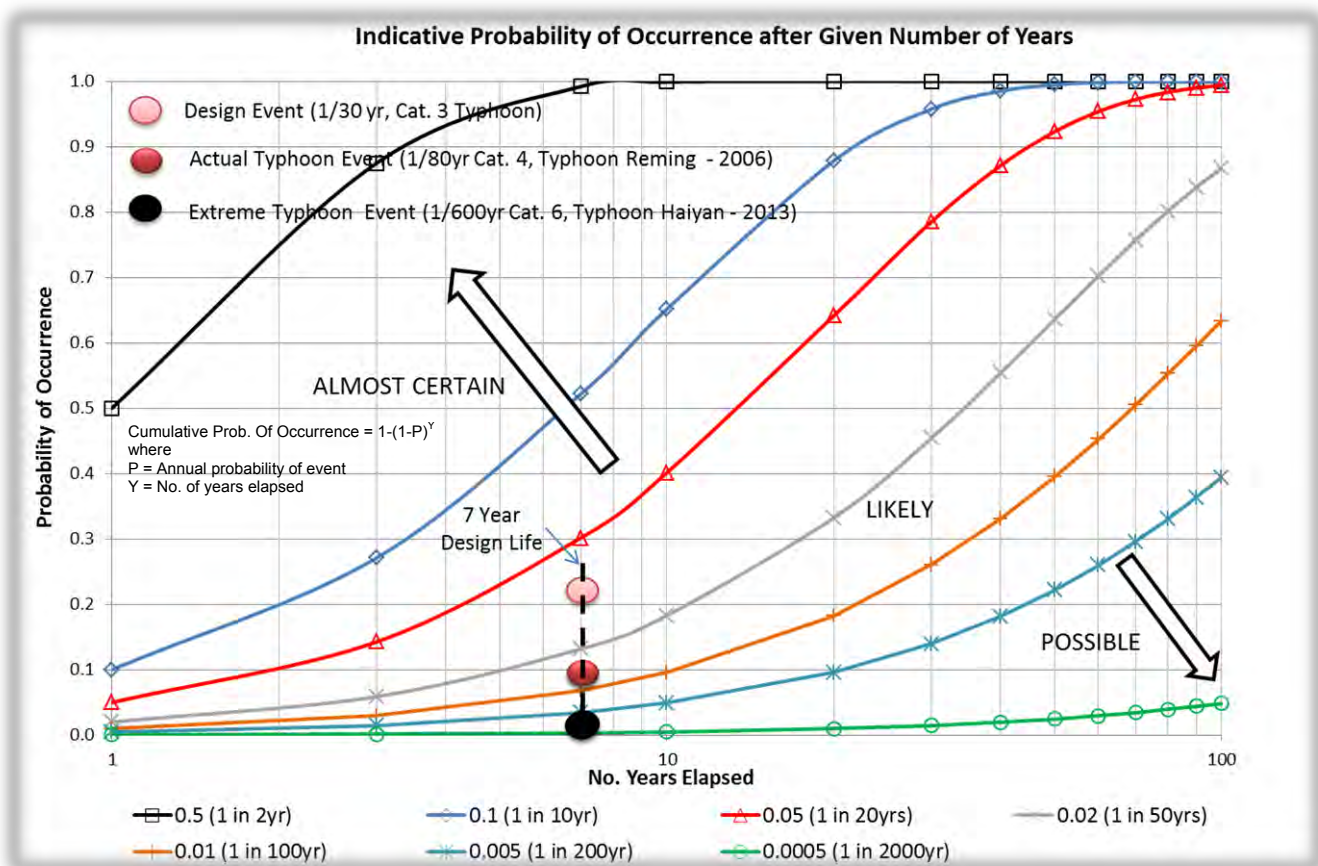


Figure 19: Probability Curves for Various Return Periods and Design Life.

It is uneconomic to design for the worst possible loads if they can rarely happen, but reflecting on the logic of adopting the selected 1/30 year design event for a 7 year design life, the client arguably adopted an unwise risk position. In this case, a cost-benefit assessment of designing for the 1/80 year event may have shown this to be a relatively good return on investment.

In general terms, risk is defined as the product of hazard/likelihood and consequence and this is the basis of what is often called the hazard-consequence matrix approach for risk assessment in either a qualitative or a quantitative context. One only needs to refer to the various National Standards, such as the Australian Standard on Risk Management (AS/NZS 4360:2004) which was first published in 1995. The Australian Geomechanics Society has developed a specific landslide risk management document entitled „Landslide Risk Management Concepts and Guidelines“. This can be illustrated using the semi-quantitative framework published by the AGS (2007). Assuming that the infrastructure ultimate limit state (ULS) condition is designed for the same outcome (i.e. damage is limited to „Medium“; unserviceable, but not destroyed), then the relative risk of designing for a range of events is presented in Table 3.

Table 3: Comparison of Risk Outcomes for Varying Design Events

<i>Design Event</i>	<i>Return Period</i>	<i>Probability during 7 year design life¹ (%)</i>	<i>Annualised Probability (%)</i>	<i>Likelihood Category²</i>	<i>Target ULS Consequence Category^{2,3}</i>	<i>Risk Category²</i>
Adopted design event (period 2006 to 2014)	1/30yr	21	3	Almost Certain	Medium (Low cost to achieve)	Very High
Super Typhoon Reming (2006)	1/80yr	8	1	Likely	Medium (Moderate cost to achieve)	High
Super Typhoon Haiyan (2013)	1/600yr	1	0.1	Possible	Medium (High Cost to achieve)	Moderate

1. From Figure 2.
2. Risk framework taken from AGS Risk Management Guidelines, 2007.
3. „Medium“ Consequence defined as Moderate damage to some of structure, and/or significant part of site requiring large stabilisation works.

Table 3 shows that the position adopted by the client in the case history was a „Very High Risk“, defined in AGS as “*Unacceptable without treatment. Extensive detailed investigation and research, planning and implementation of treatment options essential to reduce risk to Low; may be too expensive and not practical.*” Ultimately, in the case study presented here, the additional cost of carrying out the repairs before production (and thus revenue generation) was possible, but imposed considerable financial strain on the company.

If the client had chosen to invest in a more conservative risk position by designing the works to withstand the more adverse Typhoon Reming event which eventuated during the relatively short 7 year design life, then using this framework, the risk category would be „High“, defined as “*Unacceptable without treatment. Detailed investigation, planning and implementation of treatment options required to reduce risk to Low.*” With a cost-benefit analysis, this may have been a more attractive outcome for the client and project investors. Adopting the most conservative position of design for an extreme event like Haiyan, the Risk outcome reduced to „Medium“, defined by AGS as “*May be tolerated in certain circumstances.. but requires investigation, planning and implementation of treatment options to reduce the risk to Low.*” Given that the subject site was a mining type infrastructure project involving a relatively high initial capital investment followed by a slow revenue increase over a limited production life, the up-front investment required to achieve the safest outcome may have been too expensive.

As summarized in Wallis and Sandeford (2007), key points to consider relating to the risk position adopted in relation to weather events are:

- Consequences to project continued viability if an important facet (such as the export wharf) is closed down by an event outside the adopted design criteria;
- Additional cost of designing for a higher return period;
- Consider a cost-benefit study for various return periods before selecting the design standard to be adopted; and
- Remember that minimum cost may produce maximum unreliability.

Considering associated wave impacts on this type of port infrastructure and the potential for future sea level rise due to climate change, it is also possible to explore how the vulnerability of existing assets may change, and also how future projects may need to be designed to incorporate resilience to accommodate environmental change. Recognising that the relationship between wind speed and wave impact is complex and depends on many factors including the sensitivity of assets to each variable, the effects of sea level rise can be approximated using the simplistic assumption that that design wave heights are proportional to sustained wind speed. Hence, assuming that the „base case“ design wave heights adopted for the published case history of 6.4 m (berth) and 3.8m (reclamation) correspond to the 1/30 year return period „base case“ design wind speed event, then it is possible to estimate the change in risk by scaling these cases to other scenarios including extrapolation for sea level rise. Hence, normalising for the 1/30 year return period wind event and calibrating the design wave event against it, various other wave events can be scaled according to the relative size and recurrence of corresponding wind events.

Adopting a 800 mm rise in sea level from Figure 15, and correcting by 50 mm to account for the estimated rise that has already occurred since the 1990 benchmark, the effect of a 750 mm sea level rise to the year 2100 can be estimated by adding this elevation change to the design wave heights, above. This is an approximate approach because the majority of damage associated with wave action would be due to wave energy which is a function of wave height rather than wave level; however, superimposing sea level rise on storm events would undoubtedly have adverse effects considering

storm surge and flooding. Although not considered here, research work by Palmer and Räsänen (2002) suggests that the likelihood of future extreme weather events may also increase, which would be additive to the effects of sea level rise. Based on their probabilistic analysis of 19 global climate model simulations with a generic binary decision model, they estimated that the probability of total boreal winter precipitation exceeding two standard deviations above normal will increase by a factor of five over parts of the UK over the next 100 years, and that there would be corresponding implications for flooding in Bangladesh.

Assuming the impacts of wind and waves are equivalent in terms of damage potential for comparison purposes, then the normalised effect of increasing the design wave height due to sea level rise from are shown graphically in Figure 18. It can be seen from this plot that the effect of future sea-level rise (taken as being synonymous with increase in wave height when superimposed with any given event) is to move up the characteristic curve and effectively up-scale the impact of any given event in today's terms. Adopting this simplistic approach, the estimated amplifying effects of sea level rise on storm events on two assets published in the Wallis and Sandeford case history are summarised in Table 4.

Table 4: Comparison of Risk Outcomes for Varying Design Events

<i>Asset</i>	<i>Design event Return Period</i>	<i>Estimated Wave Height (Normalised)</i>	<i>Sea Level Rise, SLR (Year 2100)</i>	<i>Design Wave Height + SLR (Normalised)</i>	<i>Equivalent Design Event Return Period (inc SLR in year 2100)</i>
Berth Structure	1/30 yr (Design Base Case)	6.37m (1)	0.75 m	7.12 (1.12)	1/50yr
	1/80 yr (Typ Reming 2006)	7.96 m (1.25)	0.75 m	8.71 m (1.38)	1/150 yr
	1/600 yr (Typ Haiyan 2013)	9.94 m (1.56)	0.75 m	10.69 m (1.68)	1/700 yr
Reclamation	1/30 yr (Design Base Case)	1 (3.80m)	0.75 m	4.55 m (1.20)	1/70 yr
	1/80 yr (Typ Reming 2006)	4.75 m (1.25)	0.75 m	5.50 m (1.45)	1/230 yr
	1/600 yr (Typ Haiyan 2013)	5.73 m (1.56)	0.75 m	6.68 m (1.75)	1/1000 yr

SLR – Sea Level Rise

Table 4 shows that for reclamation structures in this region, the adverse effects of sea level rise (and inferred wave height) could result in having to design for events having return periods two or three times longer than anticipated without these future effects.

9.2 SAFETY IN DESIGN

A relatively new requirement of designers in Australia and internationally is the need to consider Safety in Design (SID). In Australia, this requirement became mandatory from 1st January 2013. The legislation requires that designers of all new structures and renovations report on the health and safety aspects of the design (a „Safe Design Report“). In addition, the designer is required to ensure „as far as is reasonably practicable“, that a structure is designed to be without risks to the health and safety of direct users or those impacted by the works. A recent example of safety in design failure relates to an incident at the Italian Port of Genoa. Nine people were killed after the container ship „Jolly Nero“ collided with a control tower. Here, it is immediately apparent that the tower position and lack of protection against ship collision (Figure 20) was a major SID shortcoming.



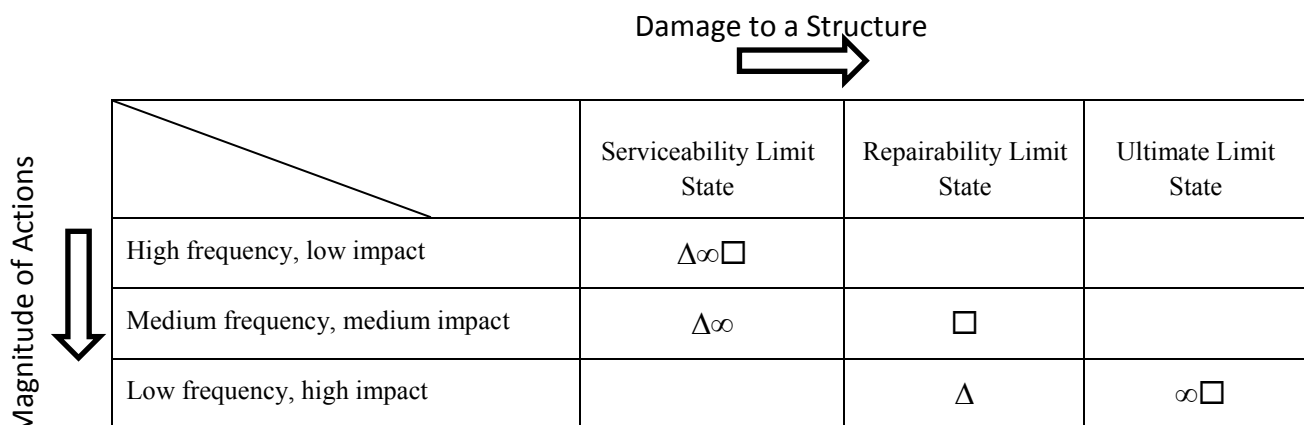
Figure 20: Port of Genoa Control Tower before and after incident (Source: Sydney Morning Herald, The Australian).

9.3 A CASE FOR REPAIRABILITY LIMIT STATE

The notion of a „repairability“ or „damageability“ limit state, is a performance based design criterion intermediate between serviceability and ultimate limit states and is becoming increasingly recognised as a way of providing resilience at reasonable cost. This approach specifies that the design is governed by limiting movements or other agreed metrics whereby the repair cost corresponding to the damage of the structure is within an acceptable repair cost and/or economic loss.

Functional objectives are to provide continued viability of structure with some interruption of service. This may involve limited damage to non-structural elements or contents and repairable damage to structure. In terms of structural performance, stresses would be anticipated as being above the elastic limit with displacements and slightly bigger than damage threshold. These concepts are most commonly applied to earthquake resistant design, which sometimes involve a further breakdown of limit states and structural importance categories.

For instance, the Structural Engineers Association of California suggests categories of „Fully Operational“, „Operational“ (light damage, economically repairable), „Life-Safe“ (repair possible but may not be economically practical) and „Near Collapse“ (structural collapse prevented, repair not possible). Potential occupancy types include „Safety Critical“ facilities (nuclear power stations), „Essential“ facilities (hospitals, emergency services) and „basic facilities“ (all other structures). The appropriateness of using design categories for varying event magnitudes can be expressed as a matrix as shown below in Figure 21.



Note: Δ Important Structure ∞ Ordinary Structure □ Repairable Structure

Figure 21: Concept of Repairability State (data sourced from Honjo, 2010).

By way of example, in relation to a seismic design on a recent port project, a minimum L.E. safety factor of 1.1 was specified for seismic global, sliding, overturning and liquefaction. Seismic bearing capacity requirements were not explicitly specified by the owner but were discussed and developed during detailed design. Design requirements included completion of a site-specific seismic hazard study; design for serviceability and ultimate design earthquake events of 1 in 100 („serviceability earthquake“) and up to 1 in 1000 („ultimate earthquake“) annual exceedance probability (AEP), respectively. Dynamic analyses considering spectral shape factor, soil dynamic and inertial loading were also required for design (Figure 22).

As design progressed, discussions ensued around tolerable safety factors for seismic bearing capacity because the apparent global bearing capacity factor of safety was relatively low (less than 1.5). This included debate on the appropriate use of input motion, appropriate factoring of peak acceleration values and the applicability of conventional (simple) bearing capacity theory for the design of gravity retaining walls including concepts of local yielding. The designers argued that full bearing failure could not develop without invoking a fully global mechanism, and that consideration of local bearing pressures, toe yielding and corresponding wall movements were more rationally assessed using dynamic analyses rather than a simplistic bearing factor of safety.

The dynamic gravity wall behaviour was typified by localized yielding at the toe and heel regions of the counterfort structure, characterized by the occurrence of plastic failure within a PLAXIS finite element model. The predominant mode of movement behaviour under earthquake loading was found to be translational rather than rotational (tilting). Critical seismic crane gauge displacement criteria were subsequently developed from these analyses.

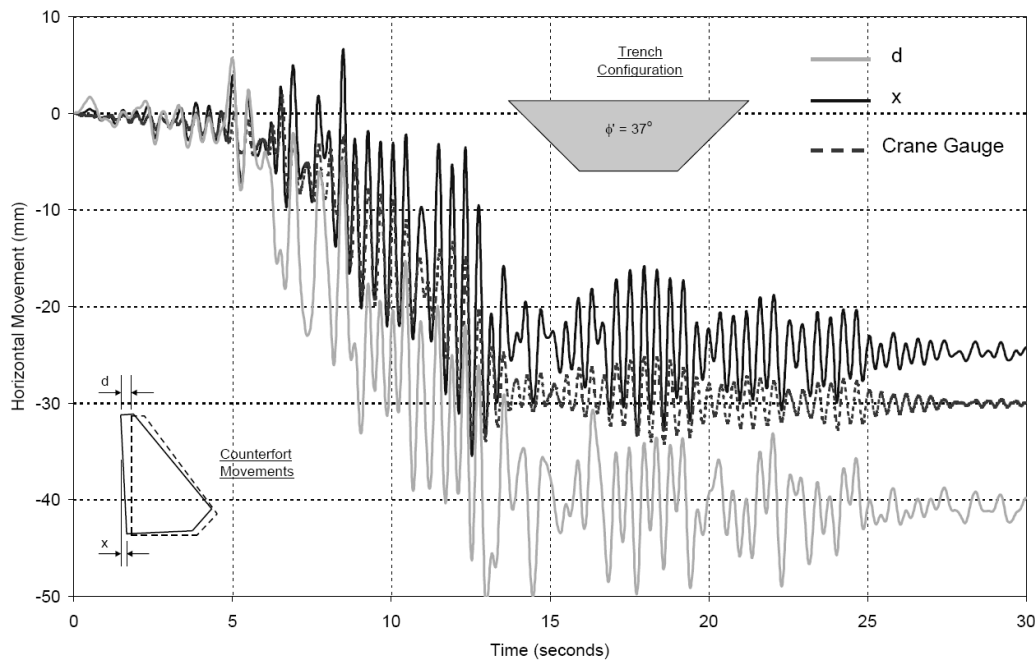


Figure 22: Dynamic Analysis of a Quay Wall Structure.

The design team successfully argued for a displacement based approach to design in lieu of an agreed factor of safety for seismic global bearing. This displacement-based seismic design enabled the client to make informed, risk based decisions around the notion of tolerable movements, damage and operational outcomes such as crane gauge movement and potential cost of repairs under different event scenarios.

9.4 GEOTECHNICAL DATA MANAGEMENT AND BUILDING INFORMATION MANAGEMENT (BIM)

In future, as the data demands on engineering projects of increasing size and complexity grow, there is an emerging need to build in scalable information sharing systems which allow remote access and sharing across diverse design and construction teams. Indeed, failing to provide such information management tools leads to potential risk related to delay, obsolete information, clashes and re-work.

Smart infrastructure in the form of digital technologies provides opportunities to improve productivity and contribute to sustainability. For example, in recent years road-mounted camera and sensor systems can detect congestion, collisions and road works, providing motorists with alerts and re-routing suggestions, reducing travel times, reducing fuel consumption and energy demand. For example, coordinated signals on Melbourne's Monash Freeway have saved 16,500 litres of petrol and led to a 40 tonne reduction in greenhouse gas emissions a day, as well as rerouting traffic, at a relatively low cost. This is a good example of how adaptive technology and feedback process can be utilised to improve the utility of existing infrastructure assets.

Starting with geotechnical data management, Child et al. (2014) describes how the traditional paper based investigate-report-design approaches can be significantly improved by efficiencies gained through centralization of data and integration across collaborative platforms. Furthermore, work by Chandler (2014) explores linkages between geotechnical data management and increasingly widespread Building Information Management (BIM) systems. BIM is gaining global popularity as a value creating collaboration through the entire life-cycle of an asset, underpinned by the creation, collation and exchange of shared 3D models and intelligent, structured data attached to them.

A graphical example of the transformation of geotechnical data management is shown in Figures 23 and 24 below. The representation shows a move from the sequential reporting process in Figure 23 towards a more fluid process whereby centralised data is constant, allowing controlled collaboration with other disciplines. In this way, the various stages of geotechnical investigation, model development and refinement, site characterization, interpretation and design inputs can be advanced and updated in parallel, where appropriate using relevant using visualizations generated by 3D and GIS packages linked to the same cloud-based data source. As a legacy, this data can also be made available in the form of a digital archive providing a repository of easily accessible as-built information, thereby adding resilience in the form of capacity to upgrade and avoid clashes.

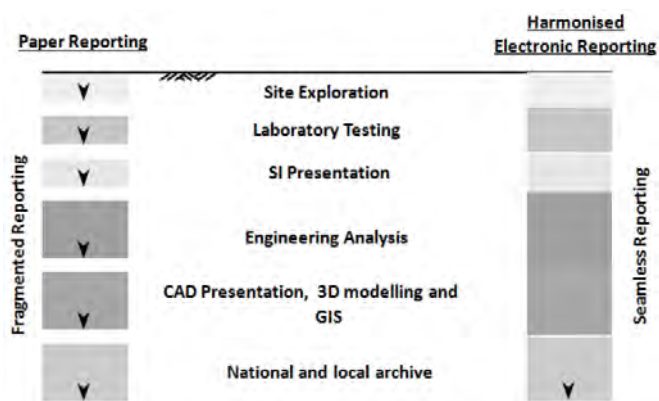


Figure 23: The traditional geotechnical data journey (Source: Chandler and Hutchinson, 1998)



Figure 24: The future of geotechnical data management (Source: Child *et al.* 2014).

Although the concept of BIM (coined in 1992) pre-dates the relatively recent advancements in geotechnical data, it has taken some time for government policies to create key driver for its use on major infrastructure projects. In 2011, the UK Government announced that all publicly funded infrastructure projects must integrate collaborative 3D BIM (with all project and asset information, documentation and data being electronic) into major projects within an overall push to introduce 20% savings across the construction industry by 2016 (estimated as £1-2.5 billion per annum). Beyond this, BIM will potentially deliver greater value in the post-construction phase, through improved ongoing management of assets at individual, portfolio and national levels by allowing for the modelling and optimization of running costs, improving energy efficiency and reducing carbon emissions – in other words improving infrastructure resilience.

The benefits of supply-chain integration in the construction sector are largely understood in terms of performance improvement, greater project „certainty“ and reduced risk. One of the key factors in achieving successful integration in design and delivery is the accuracy, effective flow and intelligent use of information, which BIM facilitates. These concepts are well aligned with Resilience Engineering philosophies.

The BIM process encourages the development and exploitation of centralized digital models enabling greater interdisciplinary collaboration, increased efficiency and optimised project performance with reduced mistakes, clashes and re-work. The general features of BIM types are described in terms of the number of model „dimensions“ (2D, 3D, 4D, etc). These are briefly described below:

- 2D – 2D Models containing flat drawing, line images or CAD renderings which depict geometric construction elements.
- 3D – 3D Models including walkthroughs, clash detection, project visualisation, virtual mock-up models, prefabrication.
- 4D – Models with the additional dimension of time. By adding „time“ to the information in the project model, it is possible to review the construction of the building as it progresses. For large complex projects or those on challenging sites, this can be particularly useful as it can be used to examine critical path activities, logistical issues such as deliveries and craneage, and to assist with building methodology.
- 5D – Models with the additional dimension of Cost. The ability of BIM models to contain cost information and quantity schedules allow costings for a given design to be produced faster; allowing option appraisals, accelerated iterative design processes and budget control.

Integration of geotechnical „layers“ into BIM systems are generally focused at the 3D level as time and cost dimensions tend to reside in the realm of construction management and delivery. The benefits of moving away from a sequential reporting-design-drafting design framework towards a collaborative design process accessing shared information is shown schematically in Figure 25 below. Considering curve 1, in a typical traditional project, as progress moves from preliminary design to documentation and into construction phases, the ability to impact the costs and functional capabilities declines, and inversely (curve 2) the costs of such changes are greater with time. The majority of team efforts enabled by CAD peaks during the construction documentation phase.

In a collaborative design process, key participants are brought in earlier, and clear goals are set and the preferred design process (curve 4) shifts efforts to an earlier point in the design cycle, spending more time up front to make better design

decisions. With this process, using BIM as a catalyst, construction documentation becomes a by-product of the design effort. Adoption of this type of process where more cost and effort is spent earlier in the project will lead to an overall increase in efficiency and optimised project performance.

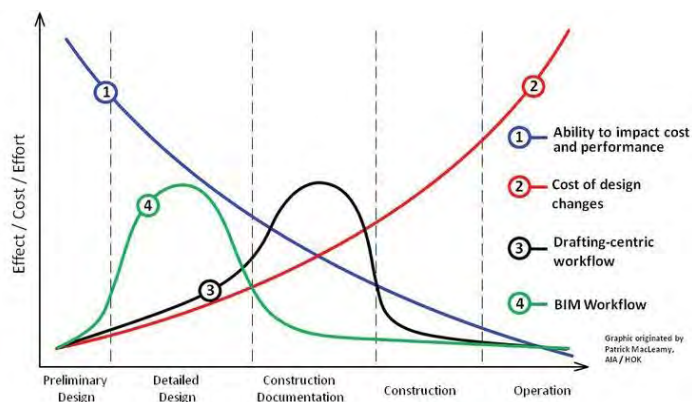


Figure 25: Design Process Curve (Source: Patrick MacLeamy, AIA/HOK).

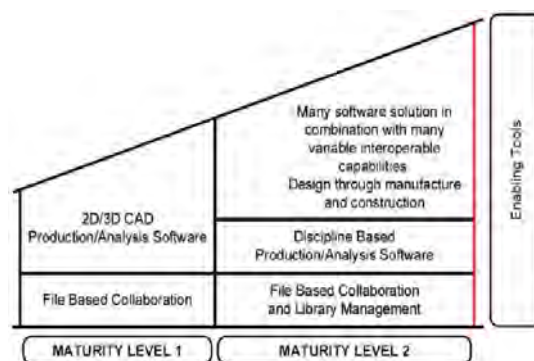


Figure 26: Summary of BIM Level framework (Source: adapted from www.bimtaskgroup.org/).

The various levels of BIM sophistication are measured in Maturity Levels (0 to 3) after the Bew-Richards BIM maturity model. The maturity model is also used to define the supporting infrastructure required at each level of capability (Figure 26). The UK government expects all public contracts to run to BIM level 2 in 2016 and onwards, as standard.

With investment only required in a limited number of digital-tools, BIM is available to anyone because principally it is more a way of working than a fixed system or product. It is the process of information modelling and information management in a team environment. Examples of Geotechnical processes could include the provision of instructions to drillers, transferring data from hand-held devices on site, remote monitoring and client access. Depending on permissions, these can create a new level of transparency and service across key stakeholders.

The availability of geotechnical information across BIM platforms during the whole process from conception, to design, construction and maintenance provides a positive risk management tool, as demonstrated by its recent use in the UK in relation to the M25 motorway project in the UK (after Chandler *et al.* 2014). The M25 motorway that circles London is one of Europe's busiest highways. In 2009, England's Highways Agency awarded a AUD\$10 billion contract to the Connect Plus consortium for future development, operation and maintenance of the M25 motorway. BIM was adopted to help accelerate the widening contract to enable opening for the 2014 London Olympics.

Tenderers for the M25 project had access to all geo-environmental data via an on online data-room integrated with the BIM compatible Highways Agency Geotechnical Data Management System (HA GDMS). HA GDMS is the principal tool for the management of geotechnical hazards and risks throughout the full life-cycle of the UK highway network from initial feasibility studies, through design and construction, into operation and towards decommissioning or redevelopment. This is by definition a continuously improving, resilient engineering system. The system contains a national model of all highways-related geotechnical assets and boreholes held by the HA and their agents, including mapping, aerial photographs and LIDAR. Related to the model are geotechnical reports, geotechnical inspections and maintenance records.

Integrating this HA GDMS data with a BIM system achieved the following benefits which helped meet the aggressive design-build schedule:

- The integrated design model helped the team visualize all above ground and underground components key elements (like retaining walls) and also related safety and access zones.
- Improved understanding of critical space constraints producing a coordinated, accurate design model allowing construction of several new cuttings and embankments under tight tolerances, while maintaining 3 lanes of live traffic in each direction during construction.
- Elimination of potential clashes between geometrically complex new elements and existing assets were identified that would otherwise be very difficult to detect using 2D documentation.

- Rapid access to critical BIM model allowing re-design and just-in-time design change ordering to optimise cost and schedule related to extensive use of steel sheetpiling.
- At construction stage, updating of the design model to incorporate additional as-built elements including new retaining walls, point clouds from laser scans, and temporary works.
- Linking the project team, including on-site construction personnel, with a consolidated, accurate construction model meaning that everyone could access the same up-to-date project information.

Ground modelling always requires interpolation and judgment when interpreting geotechnical conditions and ground risk. Work required to identify and manage geotechnical risk by ground engineers would be the same without BIM. However, the platform provides tools to assist with the understanding and sharing of this information. Ground modelling is a process of gradual refinement, often requiring multiple phases of investigation. With an initial model in place, BIM can assist with design of ground investigations and quantities for geotechnical structures and earthworks. Setting-out data can then also be fed directly into surveying equipment or extracted as 2D/3D drawings.

10 CONCLUSIONS

This paper reflects on past, present and potential future engineering demands and practices which respectfully weaken or enhance the creation of resilient infrastructure. The desired state of a resilient engineered system, project or organisation may be described as the ability of that entity to adjust its functioning in response to changes while satisfying performance, economy and safety objectives.

Remembering the ancient philosophy quoted earlier in this paper that the acquisition of wisdom involves silence, then listening, commitment to memory, practice, then teaching others, the selected case histories presented above describe the journey from trial and error based approaches towards Resilience Engineering.

Valuable lessons are shared from the past which continue to shape how geotechnical practitioners manage in-ground risk today. Linear systems of safety engineering such as Reasons Swiss cheese model and Turners incubating accidents model identify potential contributory factors in failure including misguided beliefs, decoy phenomena, information-handling difficulties, failure to comply with regulations and a tendency to minimize emergent danger.

As explored in the case history of a storm-damaged port, Resilience Engineering (as it applies to infrastructure), can apply directly to the capacity of fixed assets to absorb change. However, as case-histories show, the concept is perhaps more influential in the hands of organisations and individuals that design, construct and operate those assets, considering the people, products and processes that are involved through the project life cycle. Rather than placing multiple barriers to risk, adverse outcomes can be more effectively mitigated by recognising and enhancing the positive capabilities of people and organizations that allow them to respond to risk effectively and safely under pressure.

More recently, Resilience Engineering has emerged as a natural evolution from the principles of safety engineering and organizational reliability. Successful, highly reliable engineering organizations (and individuals) of the future will become skilled at the following basics of Resilience Engineering:

- Detecting signs of increasing organizational risk, especially when production pressures are intense or increasing – i.e listening for the „sound of the bus coming“;
- Having the resources and authority to make extra investments in safety at precisely these times when it appears least affordable; and
- Having a means to recognize when and where to make targeted investments to control rising signs of organizational risk and re-balance the safety and production trade-off.

These resilience-enhancing mechanisms may help produce an organization or project that creates foresight about changing risks before failures occur, by offering new directions for measuring and maintaining safety in complex systems. Furthermore, Resilience Engineering looks for ways to enhance the ability of systems, or more widely, organizations, to monitor and revise risk models and create processes that are robust yet flexible.

Key recommendations for Resilient Engineering are presented and include:

- Application of Resilience Engineering principles which aim to satisfy the three competing requirements of performance, safety and economy. Established and emerging tools include safety in design, BIM, safety in design and monitoring systems.
- Maintaining vigilance against the common „incubating factors“ arising from risk sources being „3Ps“, being people, processes and products.

- Considering in design increasingly adverse environmental effects such as extreme wind and wave events, selecting appropriate return intervals and selection of design events to manage risk over the range of conditions (including climate change) expected over the design life.
- Taking into account other global megatrends such as demographic changes, regional economic shifts, biodiversity and the continuing demand for transport infrastructure.
- Consideration of performance or reliability based design approaches and repairability limit states on larger projects where critical assets must be designed to remain functional, and where governing issues may relate to managing damage and repair costs. These can provide a logical framework for understanding the confidence of predicted movements and safety outcomes (serviceability and stability) and can also help with understanding of design „brittleness“.
- Moving geotechnical data management to cloud-based, collaborative platforms which are refined over the full life-cycle of projects from initial feasibility studies, through design and construction, into operation and towards decommissioning or redevelopment. This is by definition a continuously improving, Resilient Engineering system.
- Learning and teaching lessons from case histories. This will continue to be highly important to the ongoing development of geotechnical engineering and particularly in port and maritime projects. Knowledge sharing, lessons learnt registers and forensic study are all elements of a designer’s toolbox.

Dealing effectively with geotechnical risk on infrastructure projects presents challenges to designers, builders, owners and operators alike. Common issues include large and important assets sited in challenging sites where waves and water play a dynamic role. As individuals and organisations involved in the design, construction or procurement of port assets, we are all risk managers and should strive to challenge embedded assumptions and uncertainties and adopt these principles of Resilience Engineering.

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