In extremis – design

When engineers talk about designing for extremes, what do they mean and how have these circumstances changed over recent years? **Helena Russell** investigates

The solution chosen for Norway's 550m-deep Bjørnafjord is a C-shaped floating bridge which will be more than 5km long (*Statens Vegvesen, Aas-Jakobsen, Multiconsult, Cowi, Dissing & Weitling*)

The common interpretation of 'extreme' bridge design usually refers to extreme span or bridge length, tower height, deck width or remote location. But with advances in technology we are now able to deal with extremes that would have been unthinkable until recently. Extreme climatic conditions, large water depths, and harsh environments are no longer out of bounds for structural engineers; knowledge transfer from the offshore and marine industries is boosting the toolbox for bridge designers, and wide-ranging research programmes are commissioned to support some of those projects that stretch existing knowledge to the limit.

But societal changes have brought new challenges – the ubiquity of social media has made it possible for drivers to broadcast their thoughts within seconds of an incident, while user expectations about availability make any delays or closures headline news.

Designers are also increasingly required to consider the risk of extreme impacts on the safety and security of bridges – whether that be the ever-present hazards of earthquake, typhoon or climate change, accidental damage or catastrophe, or the underlying threat of malign intervention such as terrorism.

And it is not just physical extremes that challenge bridge designers these days. We also take a look at how bridge design can be influenced by less obvious extremes such as cost – whether that be on the upper or the lower end of the scale – and sensitivity of sites.

Span stretch

The seemingly inexorable stretching out of spans continues, with the need to safeguard aerodynamic stability on long spans having to be balanced against the desire to reduce dead load. And as multiple span cable-supported bridges increase in numbers, the pros and cons of this type of structure are being more widely discussed. Sites that might not have been considered suitable for bridges, whether because of topographical conditions, climate or remote location, are increasingly coming in the spotlight.

Cowi executive director David MacKenzie points out the potential pitfalls: "Span is the most obvious extreme of course, and in terms of the longest spans in the world, aerodynamics play a large part," he says. While reduced superstructure weight might be desirable from one point of view, its impact on stability is a critical consideration. "You're in the situation where you have to make the deck as wide as possible, otherwise the balance between the inertia forces and wind effects is insufficient to ensure stability," he adds.

The Çanakkale Bridge which is currently

under construction in Turkey *(Bd&e issue 97)* will create a new world record for the longest suspended span when it opens, taking span length above 2km for the first time ever. The deck design – by Cowi for design-build contractor Daelim, Limak, SK E&C and Yapi Merkezi – is the latest iteration of box girder deck design with twin box girders separated by a 9m-wide gap for aerodynamic stability, and a total width of 45m.

This move to a 2,023m-lon span is regarded as a major step forward, with Akashi Kaikyo Bridge's 1,991m-long main span having retained the title for more than two decades.

But MacKenzie points out that whilst it remains unbuilt, designs for Italy's Messina Bridge have been fully developed and in that regard, the feasibility of a much longer main span, at 3.3km, has already been proven. The main challenge for going any longer than this is not the increase in deck weight, but the impact a longer deck has on cable weight, adds Cowi director Paul Sanders. "The wire strength for Messina was designed as 1,860MPa; for a span of that size, the main challenge is that for every kilogram of deck weight you add, the cable weight goes up by 6kg. You're close to an asymptotic plateau where you just can't get any extra capacity out of the available materials to push the span any further," he says. "You couldn't really go much longer without stronger cables made of different materials, " adds MacKenzie.

Turkey's Çanakkale Bridge will have the world's longest span when complete; the twin box girders of the deck are separated by a 9m gap for aerodynamic stability

A question of cost

It seems apt to mention the Straits of Messina Bridge in the context of some of the conflicting influences on longer span bridges and more difficult environments, where the ambition for a fixed link can be at odds with its cost.

Sanders comments: "What is driving these extremes? It is the ever-increasing push to build infrastructure in more challenging environments. Messina is an excellent example; the ambition of building a bridge in that location dates back to the 1940s and 50s."

In such cases it can take decades for knowledge and technology to catch up with ambition, but as Messina demonstrates, ultimately neither is sufficient if the economic or political case cannot be made.

Recent discussions about the potential for a bridge between the British mainland and Northern Ireland focussed on the practicalities and the engineering, but as in so many other instances, cost would be the governing factor. "From a technical point of view a bridge between the two countries would be feasible," agrees MacKenzie, "but the financial case for it has not been proven. Messina was a similar case in point – it comes down to how many people want to go across it and how much they are willing to pay."

While this might be the most obvious way of judging value for money on huge infrastructure projects, sometimes other benefits can outweigh cost. Norway's ambitious E39 Ferry-Free initiative is a billion-dollar programme to eliminate ferry connections on its national highway by building a series of new fixed links, many of them using innovative technologies in extreme conditions (*see page 6*). The predicted usage figures do not necessarily make them 'feasible' by investment standards, but Norway's national and local governments are putting the emphasis on the connectivity benefits they will bring.

The time taken to travel between the main cities and other population centres will be drastically reduced, with reliability hugely improved, opening up many more options for residents in terms of work, social interaction and access to facilities, and improving supply routes for import and export of goods.

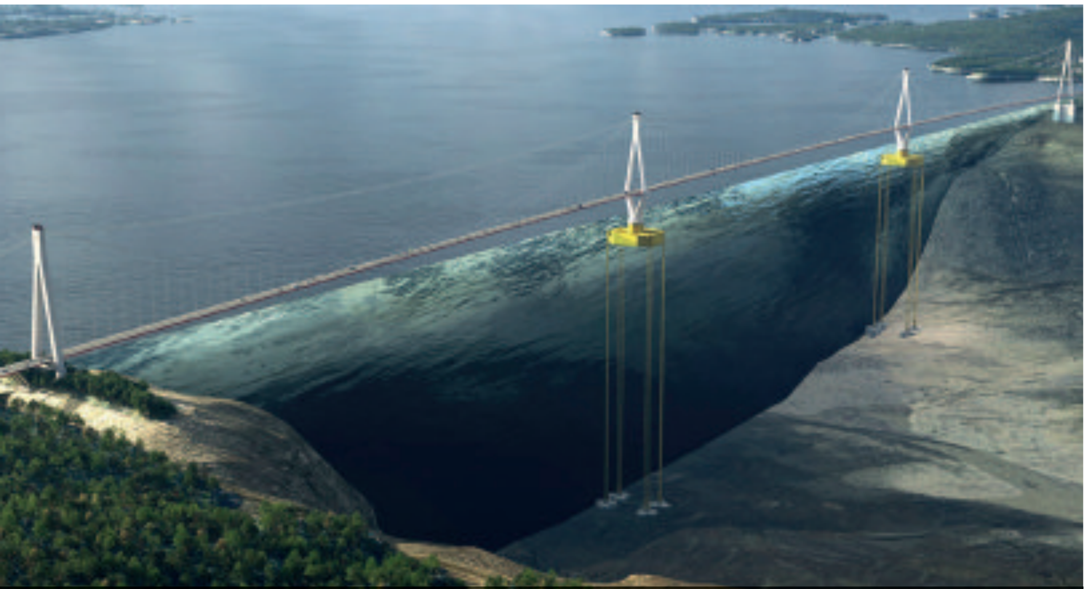
The 1,100km-long route connects Kristiansand in the south to Trondheim in the north, through the cities of Stavanger, Bergen, Ålesund and Molde. Currently the travel time is around 22 hours, and drivers have to take seven different ferry connections. The initiative will cut travel time in half by replacing ferries with bridges and tunnels, or more frequent ferries – in addition to upgrading a number of road sections on land – and will be almost 50km shorter.

Such is the impact it is expected to have on the mobility of the nation that the Norwegian government is committing substantial funds; the first section alone - the Rogfast tunnel near Stavanger, which will be the world's longest subsea tunnel when construction completes in 2026 – has a price tag of US$1.5 billion. The first of the major bridge links to be built is expected to be across Bjørnafjord, which lies on the route between Stavanger and Bergen and its design draws on oil industry and marine technology as well as bridge engineering.

Aas-Jakobsen project manager Svein Erik Jakobsen, whose consultancy is one of those involved in developing and testing concept designs for Bjørnafjord, confirms that a final decision is still necessary to progress the scheme. "These are new concepts that have not been built before; we had to develop a design basis and site-specific criteria for the different locations," he says.

"The final solutions are not quite there yet in terms of concepts and timescales and a political decision as to whether it will go ahead is still needed." This is expected next year, he adds.

Where longer bridges are necessary, and conditions allow it, multi-span



Multi-span cable-supported floating bridges are potential options for other fjord crossings planned on Norway's E39 (*Vianova/Baezeni*)

cable-supported bridges are a possible alternative. Arup's global bridge leader Naeem Hussain says that using multiple spans, with or without double cable systems, can also make long crossings more economically viable. This solution has been considered for a series of crossings in the Philippines.

"We are looking at back-to-back cable-supported spans with a double cable system – which is similar to what my colleague Matt Carter proposed for Queensferry Crossing, where we have cables that cross," Hussain says. "A double cable system could be used to stabilise the towers on a multi-span suspension bridge. When you load one span of a back-to-back suspension bridge, that span sags and pulls in the other towers on each side of it. In a classic two-tower suspension bridge the main cable is tied back to an anchorage. In a back-to-back bridge there is no anchor, but if you have a secondary cable above the main cable, with a different stiffness, it will stop the tower from leaning over. If you have very long crossings such as those in the Philippines, in big depths of water, it could work very well," Hussain suggests.

Arup is the consultant for the IPIF1 consultancy which is being funded by the Philippine Department of Public Works & Highways and the Asian Development Bank. Eight projects were considered in this feasibility study, but only three of them are likely to go ahead to construction, including the Samal-Davao Bridge and the Bataan-Cavite Interlink Bridge, for which ADB is currently inviting bids for detailed design. Although the Sorsogan-Samar Link proved technically feasible, it was not able to achieve the economic criteria of 10% economic internal rate of return, and was shelved last year. "We are confident that these projects can be built, but the question is whether the costs will actually outweigh the benefits," says Hussain. "For some of them, the cost-benefit analysis, for the small amount of traffic at this time, does not justify the bridge and in these cases you are actually much better off investing in ferry services, for example. Yes, we can do these things, but it's a matter of whether it actually fits the need."

"The Philippines suffers with extremes of many of the factors that bridge designers have to take account of. Seismicity, for example, is very high – almost as bad as California, or Turkey perhaps. We also have extreme wind conditions, with very, very high typhoon winds, and extremely large vessels coming in to Manila, with the associated ship impact risks. Finally we also have the related tsunami risk that comes with seismicity," says Hussain.

"All of those factors have been studied as part of the feasibility study looking at the Bataan-Cavite crossing of Manila Bay. This project involves more modest water depths – we are talking about 50m here, which is not that much – but the location still suffers very high seismicity, meaning that we have to design special foundations that can deal with the seismic action, but can also deal with potential ship impact from the very large container vessels that are using the port."

Design of different elements of these bridges is driven by different criteria – the superstructure design is governed by the extreme winds, and the foundation design is driven by seismic action and the ship impact, Hussain explains. "Right now in the bridge engineering world we can deal with these issues, although I would say that this project is on a modest scale," he says. "We are drawing on the research that is being done for the E39 crossings in Norway to inform our work."

Crossing point

Detailed design of the floating suspension bridge concept chosen for the E39 Bjørnafjord crossing is expected to start next year, Svein Erik Jakobsen confirms, with the Norwegian roads authority Vegvesen expected to appoint a consultant later this year. Up until now, two consultancy teams have been working in parallel on the project, but only one will be selected to take the project forward.

Jakobsen explains that to support this work, Vegvesen and the country's technical universities have rolled out an extensive programme of research aimed at increasing the knowledge base on which the new technologies will rely, and giving designers confidence to take these new concepts forward. A wide-ranging programme of site investigations is also under way to establish the environmental, climatic and ground conditions at the locations where the new bridges are to be built. "More than 50 PhD students are working on research related to this project alone – that's a unique aspect of this project," Jakobsen adds.

The E39 ferry-free project was initiated in 2009 and has been in development for more than a decade – not surprising given the fact that the main challenges that designers face is the very wide straits and very deep water. "We started by considering the location where we have the most challenging conditions – the 3.5km-wide and 1.25km-deep Sognefjord," Jakobsen explains. This prompted the development of concepts that have never been built before, combining both bridge engineering and the marine structural environment.

"You have both waves and wind at the same time, which is crucial for the behaviour of the structure, whether it's floating or not. There are no codes that govern that interaction between the wind and the waves, so we are having to develop new methods of establishing rules for dealing with this," he continues.

"Why has this not been a problem before? Usually structures such as those used in the oil and gas industry don't suffer from interference with the mainland. In general it's easier to understand how the waves will behave because they are not influenced by local conditions, by the bathymetry and so on. At the shoreline, however, they are influenced both by bathymetry and the wind, and the wind is also influenced by the topography. It's very complex. As well as the induced waves, which are influenced by local factors, you have swell waves, which are generated a long way away from the site, and that interact with winds at the site. "

The fjords are surrounded by high mountains which cause turbulence; Jakobsen says that the monitoring equipment present has recorded the largest ever vertical winds, which have direct implications for deck behaviour.

The monitoring and investigations are particularly important in enabling designers to consider these site-specific environmental loadings. "This is vital since we are looking at very unusual concepts such as 5km-long floating bridges," Jakobsen continues. "The longest floating bridges that currently exist are around 1km.

"The knowledge gained through this work will add value to the existing codes, with respect to these types of structures – we will close the missing links in terms of understanding," he says. "The main benefit is that we are looking at bridge designs that may open up opportunities for strait crossings all over the world; those that at the moment may not be feasible."

The first of the extreme bridge crossings is planned to be built at Bjørnafjord, as this will have a substantial impact on economic activity by improving access between Bergen and Stavanger. The concept design was selected last year after several years of research and development, and there is expected to be an announcement later this year to confirm which of the two consultants will take the design forward to prepare the tender.

Two consulting teams worked independently to assess the shortlisted options for a floating bridge; both concluded that the most suitable concept was a C-shaped floating bridge which will be more than 5km long and will cross the 550m-deep fjord. The most important criteria were structural reliability, functionality, cost and aesthetics.

The team that is chosen will develop the basis for the tender specification, before the government takes a final decision whether to proceed with the project or not.

Feasibility studies are also starting into the crossing of Sulafjord, Jakobsen reveals. "This is a very harsh environment – much more open to the ocean – and it will be even more extreme than Bjørnafjord. Usually the fjords are sheltered by islands and so on, but Sulafjord is not at all, so it will be quite exciting!" he predicts. A big site investigation is also under way at this location; the water depth here is about 500m deep, but the crossing will be shorter than Bjørnafjord.

A decision on bridge type for this location is not expected before 2022; a framework contract involving three companies was awarded at the start of this year, and concept development will follow a similar process to

CLIMATE CONTROL

Extremities of climate and environment can influence material choice when durability is a central concern. Dar senior associate Wassim Dergham explains the conditions that drove design of almost 50km of viaducts for two new highway links in Kuwait (*Bd&e issue 91*).

"The location of the Sheikh Jaber Al-Ahmad Al-Saber Causeway experiences very severe environmental conditions – it is a marine environment with high chlorides, high humidity and big variations in temperature. Temperatures can vary from 21°C to 60°C, with a high of 63°C recorded during construction of the bridge," Dergham says.

This severe environment affected the selection of materials, particularly the concrete mixes and the choice of aggregate. "Gabbro aggregate, a type of granite, was selected as aggregate rather than limestone materials which were not suitable for the harsh environment. The design also specified stainless steel rebars in the concrete that was exposed to the marine environment, in the piers and the pier caps," he adds.

A controlled permeability formliner was used for concrete that was cast in place, which improved the density of the concrete by allowing water to escape during curing, but not cement. "The durability requirement for the concrete was very high; it's a 100-year design life for the bridge," he explains.

Another aspect where material choice was driven by the corrosion climate was the safety barriers on the viaduct. These were made of galvanised aluminium sections; the challenge was to achieve the high galvanisation content necessary to resist corrosion in this environment.

In addition, the design had to take account of possibility that bored drivers might speed up, given the extreme length of the crossing; hence the safety barriers are designed to contain vehicles travelling at 140km/h, rather than the norm of 100km/h.

The local climate also creates difficulties for maintenance, says Dergham. Sand migration on the bridge during storm conditions can sometimes be at such volumes that lanes become blocked.

Extreme conditions at the site for Tintagel's new footbridge demonstrate how the design of small bridges can also be impacted (*Shutterstock*)

that which was used for Bjørnafjord.

"It's a difficult question as to the type of crossing that will be chosen for Sulafjord," muses Jakobsen, "but I don't think it will be the same as that which was chosen for Bjørnafjord. The main reason the floating suspension bridge was chosen for Bjørnafjord was down to the cost," he says. "But at this site the conditions may demand a very different solution. In fact some of the concepts that were ruled out on that project due to cost might be applicable here – such as the floating tunnel for example."

Small scale

It would be wrong to assume that extreme conditions only impact on design of the world's largest bridges, or those in the most remote locations. A case in point is the 67m-long footbridge that was built for English Heritage at Tintagel in Cornwall, as Ney & Partners project manager Matthieu Mallié discusses.

"Several conditions made it extreme, relating mainly to its location and the topography at the site," he explains. "For a start, the site was not accessible by road, only by sea, so from the start we had to consider the design in terms of construction technology that would work at this location. That is why we chose to use an aerial crane, which is more traditionally used for construction of ski stations in the mountains.

"So the design was tailored to allow it to be built this way, and that's why we decided to design a cantilever. We knew that we couldn't put scaffolding or any temporary supports under the bridge, so we planned to build from the cliffs outwards," he recalls.

The remote location meant it was impossible to bring the bridge as one piece, or even several large pieces – it had to be divided into small sections of maximum four or five tonnes that could be lifted by the cable crane.

The accessibility of the site and the topography had a major influence on the bridge design, Mallié confirms. "Without those challenges, we probably would have chosen a different design."

An added complication was the protected status of the site's environment, landscape and archaeology – a triple constraint for the site as it demanded design approval from a number of authorities. "We had to convince many different bodies with the quality of our design," Mallié says.

Minimising the size of the foundations was the key to reducing the bridge's impact on the archaeology and protected habitat. "By splitting the structure into a lower and upper chord the main support was at the lower chord, some 4m below ground level. The abutment was minimised as far as possible, and the designers created a support point on sound rock, which formed the abutment."

This decision also reduced the impact on the natural environment, where action was needed to prevent the bridge from interfering with nesting cliff birds, rare mosses growing on the cliffs and so on. Minimising the support point contributed to this.

Whether or not Mallié's team achieved a design that would not conflict with – perhaps even enhance – the beautiful setting is subjective, he acknowledges. "At least we succeeded in convincing the relevant authorities," he says. "That's also one of the reasons why we chose a transparent truss structure."

Choosing a low profile superstructure – the 'arch' that became a cantilever – kept it

Extremes of climate are present at the Tintagel site; the two major issues were the corrosive environment and the wind (*Hufton & Crow*)

from competing with the landscape and the ruins of Tintagel castle. A cable-stayed or suspension bridge would have created unavoidable visual conflict.

But extremes of climate are also present at the site, Mallié reveals, with the two major issues being the corrosive environment, and the wind. The Atlantic coastal environment lends it the highest corrosivity classification, C5M, and the extreme wind environment demanded specialist advice.

To protect against corrosion, special materials had to be used for the structure, including a Duplex stainless steel with the highest possible resistance to staining.

The exposed location of the bridge, combined with the topography of the coast, creates a wind tunnel effect at the site, with winds gaining speed along the shore. RWDI was contracted to model the site and assess the aerodynamics of the design, and vice president Ender Ozkan explains: "The bridge is in a very windy spot, spanning across a gorge on the coast which makes it more extreme in terms of the weather impact. Initially we did extensive work to model the topography of the area – the cliffs and the island on which the bridge is located – to determine the way that the wind is directed and accelerated by the cliffs. The cliffs steer the wind and redirect it from horizontal so that it is actually blowing upwards as it reaches the bridge. It also speeds up because of the cliff effects," he says.

Extensive sectional aeroelastic modelling was used to determine not just that the bridge could withstand the average mean wind speed, but also that it would be stable against some of the aeroelastic problems that bridge decks experience, such as buffetting and so on.

"Wind tunnel testing can capture the gusting effect of the site very well compared to computer models," explains Ozkan.

"We built a physical scale model of the whole cliff and the island – measured the turbulence and the movement for the wind direction at different positions along the deck, and then we used that to build a sectional model of the deck at a larger scale, which was put in a wind tunnel on spring supports."

"We were on the team from the very early stages, which meant that the design did not really progress without reference to the aerodynamic impact of any changes," he says – a process that works efficiently. "We've worked on other projects before – some long span bridges for example – where we are brought in at a later stage and the designers have to go back and change the deck design in response to what they find out from the wind tunnel testing and so on," he explains.

Changing nature

Analysing and resolving aerodynamic behaviour for a bridge design can be extremely onerous, and is one sector where computer modelling still has some way to go, Ozkan reveals. "Computer simulations of wind are still relatively new. It's only really in the last five or six years, since the arrival of super-fast cloud computing, that we've been able to explore computational fluid dynamics at any really big scale. But even with cloud computing you need a really big team of modellers.

"For example, if you're trying to capture a large 2km^2 area, you have to split down that large domain into blocks of 20cm by 20cm, which is several hundred million cells. It can be done, but the money that you would have to pay for the cloud computing capacity at this time would effectively be more than the cost of doing a wind tunnel test. Very small details on the bridge such as parapet details, something on the soffit and so on can really change the behaviour of the deck in flutter, or vortex shedding. But the cost of trying out alternatives, with wind directions from multiple angles, is still quite expensive.

"We have a big team working on this, because we know that ultimately it will be more effective in the long-term to use computer modelling. But at the moment we use it mainly in the early stages of design, when a client wants a rough idea of how a proposed bridge design will behave aerodynamically."

On demand

Meeting demand for availability when high winds or storm conditions blow in is an ongoing challenge for bridge owners. Drivers' expectations are higher than ever before, and social media makes it easier than ever for them to voice their frustrations when bridges have to close. Sometimes closures are forced by wind speeds, although today wind shielding tends to be fitted to decks in an effort to eliminate this problem.

"Wind speeds aren't going up, they are just more frequent," believes MacKenzie. "Vortex shedding can of course be designed out, but wind effects are becoming more significant, and wind shielding will be more often required because of the ever-increasing demand for reliability of transportation links."

Ozkan agrees: "The new Queensferry Bridge in Scotland is designed to be operable in pretty much all weather conditions. The logic is that if you can get on to the bridge via the unshielded ramp, you can cross it thanks to the wind shields on the deck. They do have some closure protocols, but it's a bridge that can withstand quite extreme wind events."

However he notes that its recent shutdown demonstrates that it's not always the most obvious conditions that count as extreme, sometimes problems such as ice accretion on cables cause unexpected closures. "And these days with social media, it's much higher profile, as soon as a bridge closes for any reason it's there on the internet – this social change in our society means engineers have to think about other extremes, not just the usual things. In the past there might have

The Ozman Gazi Bridge in Turkey features a fire suppression-system on the main cables and a seismic-isolation system on the sea bed

been publicity, but it would only be a local thing," he says.

Expert Christos Georgakis, who is professor of structural dynamics and monitoring at Aarhus University, echoes this. "One of the big issues with the cables these days of course is icing – this was not a big issue in the past, it was never discussed. It did happen, but it is happening more these days because of the rise in the number of cable-stayed bridges, and the number and arrangement of the cables," he says.

"Twenty or thirty years ago there were many fewer cable-stayed bridges and where icing problems did occur, they were treated very differently. Before Denmark's Storebælt crossing was built, people had to line up and wait, sometimes for hours, to get a ferry. When the bridge opened, it was an amazing thing just to be able to drive across. So if the bridge had to close for an ice event, it was only what people were used to – having to queue up and wait for it to reopen. These days there is much less tolerance, and people are less willing to wait. The use of social media contributes to this with any closures being reported immediately," he adds.

Georgakis also believes that the conditions under which ice accretion occurs are happening more frequently. "Perhaps this is a wave we are going through that somehow has something to do with climatic changes. It's a big design issue, and lots of resources are being expended on it."

He reveals that he has spent the last few months working 'almost exclusively' on this issue in relation to the Gordie Howe International Bridge which is planned for construction over the Detroit River between the US and Canada. "We've spent a lot of time discussing how we can address it. There's no obvious solution: I work a lot with cable manufacturers – there's no way to avoid ice and snow accretion, you have to manage it. It's very difficult to get rid of, and it accretes in a very difficult and unpredictable way. You can put all kinds of coatings on the cables, but then you get a little scratch in it and the ice will accrete at that location. All the effort these days is going into managing it."

There are two different areas of focus – risk assessment, and risk reduction, he says. The first is long-term prediction, evaluating the probability of it happening, and predicting when it will occur and under what conditions. The second is real-time prediction, monitoring what is happening, and whether accretion is likely to occur as a result. "These systems are getting much more sophisticated, and now we are even having discussions about whether we could introduce some kind of artificial intelligence – trained systems that could predict the possibility of accretion based on the conditions," Georgakis reveals.

There are different options for managing the problem, including ice and snow retention systems, which keep the ice on the cables until it melts or breaks into smaller pieces. This works on the same principle as fins on ski chalet roofs, which break up the snow as it travels down the roof.

Other methods involve mechanisms to shake the cables; a rotating component on the cables; mesh on the outside which can be vibrated to shake the ice off and so on. "There's no perfect system out there right now, but there are attempts to develop something," he says.

However cost can be an issue. "Putting a profile on the sheath of the cable is very good for what it is intended to do – it prevents accretion, it's very aerodynamic and stable, but unfortunately it is very expensive to manufacture. You could put something cheaper on the outside, but it would cause drag on the cable; or you could put some rotating or movable element on the outside but it would cause corrosion – there's always some sort of drawback," concludes Georgakis.

Under attack

But it is not just natural phenomena that pose a risk to cables – man-made hazards both accidental and deliberate are also challenging designers. Cables can be an obvious target for terrorists wanting to disrupt transportation systems by putting bridges out of action, and bridge owners are increasingly having to consider how best to prevent damage.

Cowi's David MacKenzie explains: "Extremes in security are a big thing at the moment, although we aren't able to talk about them in any detail due to the obvious sensitivity of clients. Eurocodes do bring in the concept of accidental loading, which is something that needs to be thought about; historically, bridge design would follow the loads of the code and that was it."

But it's not just cable vulnerability, and not always under malign circumstances, he continues. "In terms of robustness you have to start thinking about what happens if one component fails or needs to be replaced. For example on some cable-stayed bridges you will have hold-down bearings at the end, and you have to consider what would happen if they were to suddenly fail and you had traffic on the bridge. So, assessing the vulnerability and the criticality of that component - and indeed all components - is really important. If it has any weaknesses or deficiencies, those are what you really want to be aware of because of the consequences of them failing."

Georgakis continues: "The easiest thing for a terrorist to do would be to get a vehicle full of fuel and park it next to a cable or a set of cables, set them alight and put the whole bridge in danger. This didn't really count as a major issue 20 years ago, but these days there is a lot of discussion about it, and everyone is doing testing and thinking about protecting cables from fire, explosion and so on.

"One thing we do now is build even more redundancy in the design – we now have two-cable redundancy built into the designs of some new cable-stayed bridges, to allow a redistribution of load if there are any failures. It is not difficult to do, it just makes the design more expensive because it requires more cables, which leads to a heavier girder and so on."

"We have also been looking at how robust steel towers are to fire, and to collision," MacKenzie adds. There have been a number of notable accidents in the past, both on and close to bridges – the most recent being the high-profile explosion of the chemical tanker Stolt Groenland in Ulsan Port below the Ulsan Bridge in South Korea last


Last year a chemical tanker caught fire under Ulsan Bridge in South Korea (*Shutterstock*)


Tower foundations for the Chacao Channel Bridge in Chile, which is being built close to the site of the largest earthquake ever recorded

September. The dramatic explosion and fireball, which was caught on dashcam by a car on the bridge, was within metres of the deck. This underlined the potential for disaster, and reinforced the wisdom of implementing measures on recent bridges. Comments MacKenzie: "On the Ozman Gazi Bridge in Turkey we designed the main cable and suspension system for the possibility of fire, and introduced fire suppression systems, which are effectively 'sprinkler' systems attached to the main cable."

Shake down

Unpredictable forces are not always accidental or deliberate; for structures in seismically-active zones they are a central consideration, but the focus is more often below ground. Cowi's Paul Sanders recalls seismicity being a big concern in the design of the 3km-long Ozman Gazi Bridge across Izmit Bay. "Here the challenge was the foundations, and the solution was to design a seismic isolation system on the seabed using rubble to create a slip plane between the seabed and the underside of the foundations," he says. "We designed the main towers to slide on the seabed and displace by around 1m, which is similar to what happened to the Akashi Kaikyo Bridge in Japan, which was under construction when the Kobe earthquake struck."

Design of Chile's Chacao Channel Bridge, which is currently under construction, employed a similar approach, confirms Svein Erik Jakobsen of Aas-Jakobsen. His firm is working with consultant Systra for the design-build contractor Consorcio Puente Chacao, led by contractor Hyundai Engineering & Construction. "The most challenging aspect has been the seismic forces as it's a hotspot," he says. The site is close to where the biggest earthquake ever recorded took place, and it has been difficult to get the right solution to resist both the extreme seismic loads, and the behaviour of the earthquake itself. Designers must consider an event with a lot of energy in very high periods, with foundations that can move relative to each other in all directions.

One difficulty is agreeing the upper bounds, he adds. "Of course you have codes and regulations for what you need to design in terms of return period. But the client will always say 'what happens if the earthquake is bigger?' We have to find agreement between the owner, designer, contractor and so on." The project has already been in development for almost a decade, and the earthquake history for the site had to be updated after the 2015 event which was more severe than had been predicted.

The most obvious extremes for foundations are in flood-prone regions such as Bangladesh, notes Sanders, and on projects such as the Jamuna and Padma bridges, offshore construction techniques assisted with construction. Experience from past projects is being used for the foundations of a different type of infrastructure, Sanders reveals. "We've recently been designing foundations for a high-voltage power line across the Padma River; it's a 400kV line which uses pile-driving technology adopted from the oil industry. The line has enormous foundations with 3m diameter piles going to about 100m below the river bed, and each pile alone weighs about 400t," he says. The piles are designed to address very challenging environmental conditions, including scour levels down to -57m, which coupled with the seismic requirements, vessel impact and so on are very demanding. "With towers that extend to about 150m high above the water, you have something approaching a 200m-long cantilever," Sanders continues.

"These days the tools are readily available to analyse such structures and this is all being done to produce economies in the design. But without these tools, I wonder whether it would have been at all possible to design these bridges properly? We certainly would not have been able to do it on an economic basis. With the scour effects that we are seeing, the feasibility would certainly have been called into question and people would have just said – look it's too challenging, let's think about building the bridge somewhere else."

Marco Petrangeli of Integer reiterates the issue of extreme ground conditions – and points out that they are not always in the most obvious locations. "There are lots of places where you cannot build a bridge because you cannot stabilise the ground, it is simply overwhelming and instead you need to relocate or increase the span. We have plenty of examples on the Italian Appennini, and I am not sure if any new solutions exist."

His experience in Constantine in Algeria is particularly telling. He recalls working on a project more than a decade ago to salvage the Sidi Rached Bridge, Africa's largest masonry arch and a national monument, from slope instability, and notes that the ground subsequently restarted its motion. Further intervention is likely to be necessary, Petrangeli suggests, with the adjacent, subsequently-built Salan Bey Bridge also impacted.

Future proof

Past experience shows that bridge designs will continue to evolve to meet whatever


Future water level rises have to be considered in the design of bridges with restricted navigation clearance, such as Schuman Bridge in Lyon, France

technical challenges arise – but the pressure to reduce consumption and the zero carbon initiative means that engineers have to adapt, says MacKenzie. "It can't just be business as usual – we have to consider how we use materials not just in terms of cost, but also carbon usage. There's a particular imperative with the zero carbon initiative to think very carefully and that's going to drive where we go in the future. "For example we will be looking at whether it's more effective from a materials point of view to design a suspension bridge which requires a huge anchor block, or choose a cable-stayed bridge instead. The use of materials will be another important, aspect of the design process," he says. "There's a need to design for increasing water level due to climate change, and that's certainly impacting on clearances under bridges," adds Sanders. "But at the moment we don't have a huge amount of data to underpin the allowances that we are making in the design process for the increasing water levels. With a design life of 100 years you're in a different situation to design of buildings, for example, where you are only planning for a life of 20 or 25 years."

One example is the Schuman Bridge in Lyon, he says. "The challenge was to design the deck to meet both the lowest depth we could have for the roadway and the minimum headroom below the bridge. Of course if you have surge conditions and rises in water level you're not going to be able to get underneath bridges like this, and the risk of impact to the bridge deck becomes much more prevalent."

ON THE EDGE

Bridge design for extreme locations often demands special consideration – whether it serves high or low tech construction. Material selection for the new bridges on South Africa's Wild Coast Highway, for example, was largely dictated by location. Consultant Smec general manager for structures, John Anderson explains: "The availability of materials becomes a big consideration – how far away are your aggregates, for example, if you are considering a reinforced concrete bridge. Also if the quality of local aggregates is not good then it could become a problem in terms of long-term durability of the bridge – could you even use them? On the Msikaba Bridge for example, there is the challenge of ensuring that the concrete for the two towers will match in colour because of the need to source aggregate from a number of different quarries.

"If you have good quality materials available, then in situ construction becomes a possibility.


Availability and quality of materials is a key issue at remote bridge sites such as those on South Africa's Wild Coast Highway

If not, then you have to start thinking about precast concrete or structural steel, but as soon as you do that, you've got to start looking at where the units are going to be fabricated and how you are going to get them to the site. The transportation cost is going to have a big influence," he adds.

At the other end of the scale, the need for bridges that are easy to build and maintain, to serve remote communities, is now widely recognised. In such cases it is poverty that is extreme, and simple structures are required so that they can be built by local people using basic materials and without the need for special machinery. The designs must also be easy to replicate so the communities that use them can carry out any repair or replacement. Charities such as Bridges to Prosperity work with donors and volunteer engineers to design, build and maintain durable and environmentally sustainable bridges that will provide safe access for generations.

These pedestrian footbridges are designed to be resilient to extreme weather events, and are built with locally sourced and donated materials. Each footbridge costs approximately US$60,000, taking into consideration the variable topographic and geographic conditions, community contributions and logistical challenges in each country and region.