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S E C E D

NEWSLETTER

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In this issue

Nigel Priestley (1943–2014)

Editorial Introduction

Professor Michael John Nigel Priestley passed away in Christchurch a year and a half ago, on 23rd December 2014. Priestley's name will need no introduction to most readers of this newsletter. Along with Professors Park and Paulay, Priestley was one of the famous 3 P's of New Zealand earthquake engineering. His career straddled New Zealand, California and Italy, academic research, teaching and design practice, experimental and analytical engineering. He was a keen sailor, a tramper and a lover of the outdoors, a classical guitarist and a poet.

For this special issue of the SECED newsletter, I asked some of Nigel's ex-students and friends to contribute short pieces on Nigel's legacy and personal reflections of working with him. The first three included herein, provided by Timothy Sullivan, Katrin Beyer, and myself, summarise Nigel's contributions to the fundamentals of seismic design, masonry and analysis. Of course, this short list of topics is non-exhaustive – most obviously missing are his seminal work on reinforced concrete design, bridges, and high-seismic performance precast concrete systems (through the PRESSS research programme). Nigel's name crops up in many different areas of seismic and non-seismic design where we wouldn't necessarily expect to find it, as noted in the fourth short article, provided by Nigel's long-time friend and collaborator, and ROSE School co-founder, Michele Calvi.

Nigel delivered the ninth Mallet-Milne lecture, "Revisiting myths and fallacies in earthquake engineering" in 2003. Edmund Booth gave the official vote of thanks that night, and he kindly provided the text of his speech to republish in this newsletter issue. Ian Kirker also recalls Nigel's Mallet-Milne lecture in his note written on behalf of the Institution of Professional Engineers of New Zealand (IPENZ) UK Branch.

The last part of Nigel's career was marked by the occurrence of a series of earthquakes in his adopted hometown of Christchurch, New Zealand. He was asked to contribute to an Expert Panel for the Canterbury Earthquakes Royal Commission that investigated building performance in the earthquakes. In the last contribution to this summary of Prof. Priestley's legacy, Didier Pettinga describes his contribution to this Royal Commission.

Contributions to the Fundamentals of Seismic Design (Tim Sullivan)

In a future text on the history of seismic design, I would expect that a discussion of the fundamental developments made by Nigel Priestley will be very prominent. The very first seismic design provisions in building standards (e.g. Italian regional decree of 1909) recognized that earthquakes impose horizontal accelerations at the base of buildings, and since force equals mass times acceleration, buildings should be designed to resist equivalent lateral forces (Fi in Fig.1a) set as some percentage of the building weight (e.g. 10%). Later, after accelerograms were recorded, the concept of the earthquake response spectrum was introduced (Fig. 1b) and thus the importance of a building's dynamic characteristics on apparent seismic demands was revealed. Then, as time went by, more earthquakes occurred and lessons were learnt. It was observed that some buildings didn't collapse in earthquakes even though equivalent elastic force demands would have exceeded their lateral yield strength ($F_e > F_y$ in Fig. 1c). This observation illustrated that ductile buildings, which can deform laterally to displacement demands several times those of the yield displacement, perform better in earthquakes than brittle buildings. Seismic design guidelines developed to reflect this by setting the design force equal to the equivalent elastic force divided by a ductility-capacity-dependent reduction factor. In addition, capacity design methods were developed to ensure that ductile mechanisms would develop instead of brittle mechanisms. Empirical force-reduction factors (known in Europe as behaviour factors, q in Fig.1c) were set as a function of building typology, recognizing that certain building typologies (e.g. steel frame structures) tend to be more ductile than others (e.g. unreinforced masonry structures). This approach, which is often referred to as the equivalent lateral force (ELF) method, is still the basic seismic design method in international codes to this date.

Priestley contributed to educating people about these fundamental earthquake engineering concepts, as can be appreciated by the well-known text he co-authored with Tom Paulay in 1992 entitled "Seismic Design of Reinforced Concrete and Masonry Buildings" (Paulay and Priestley, 1992). This text continues to be sold by Wiley and contains valuable guidance on the seismic design and detailing of reinforced concrete structures. Nevertheless, when I asked Nigel to autograph my copy of the text in Pavia in 2001, he wrote beside his signature "Sorry it's out of date". This apt comment lies in my book because the year after the text by Paulay and Priestley (1992) was published, Priestley made a new publication that, in the field of earthquake engineering, could be likened to the boy who points out that the Emperor is wearing no clothes.

In his 1993 paper entitled "Myths and Fallacies in Earthquake Engineering", Priestley (1993) demonstrated that the ELF method is fundamentally flawed because the ductility capacity (and moreover the displacement capacity) of a single structural typology cannot be rationally defined because it changes greatly with changes in structural geometry and material properties. Furthermore, for reinforced concrete structures, Priestley pointed out that even the initial period (required as an input to the ELF method in order to identify the elastic spectral acceleration and force) cannot be reasonably estimated at the start of the design procedure since the stiffness of a RC structure depends on its strength, which is not known until the final design force has been obtained. In response to these and other shortcomings of so-called "force-based design" approaches, Priestley proposed the Direct displacement-based seismic design (DBD) method.

Priestley led the development of the Direct DBD method, together with Prof. Gian Michele Calvi (IUSS Pavia, Italy) and Prof. Mervyn Kowalsky (North Carolina State University, U.S.), in the two decades following the 1993 paper, explaining the details of the approach in a leading text on the "Seismic Design and Retrofit of Bridges"

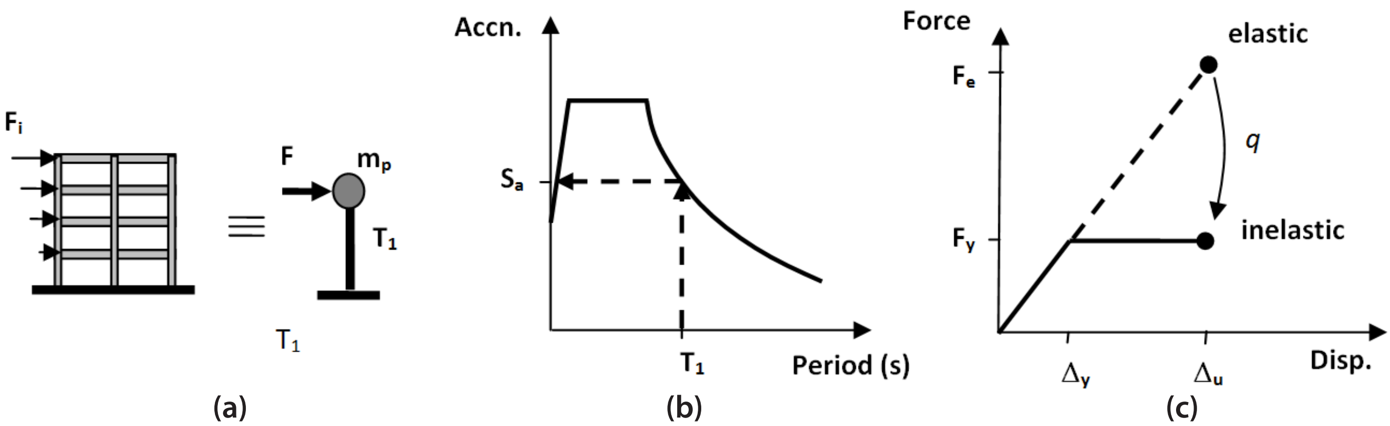

Figure 1: Conceptual overview of the equivalent lateral force design procedure (from Sullivan, 2013). (a) Equivalent SDOF system with initial period, T_1; (b) Use of elastic acceleration response spectrum; (c) Reduced design forces to allow for inelastic response.

(Priestley et al., 1996) in numerous international journal publications, in the 2003 Mallet Milne lecture (published as a monograph; Priestley, 2003) and in a comprehensive text in 2007 entitled "Direct Displacement-Based Seismic Design of Structures" (Priestley et al., 2007). The Direct DBD method revolutionizes seismic design by putting the focus on the control of displacements, which are more closely correlated to damage than forces. The approach utilizes the secant stiffness to a target performance point and encourages the designer to set the strength proportions they prefer, rather than be dictated by the results of a structural analysis software. The international recognition of the relevance of the 2007 text is perhaps best expressed by the comments made by Graham Powell (Emeritus Professor at UC Berkeley) on the book "It is rare for a book on structural engineering design to be revolutionary. I believe that this is such a book. If you are involved in any way with seismic resistant structural design, this should be on your bookshelf, and you should read at least the first three chapters".

Many of the developments to the Direct DBD method were made in Pavia, during Nigel's time as Co-Director of the ROSE School, Pavia, Italy, where I was fortunate enough to study under his supervision. Development of the method has continued after 2007, and in 2012 we released a model code on the Direct displacement-based seismic design of structures (Sullivan et al., 2012), effectively illustrating the extent to which the method has now been developed, covering a wide range of structural typologies and technologies. The Direct DBD procedure has also begun making its way into building standards (such as the NZS 3101 (2006) and the draft Australian bridges standard, DR AS 5100.2-2014) and it is understood that the subject of DBD is now being carefully considered by Eurocode 8 workgroups and committees.

Priestley's contributions in earthquake engineering were not limited to the fundamentals of seismic design (as can be gauged by the other notes in this publication) and nor were his contributions to the fundamentals limited to Direct DBD (for example, he also made important observations about capacity design, pointing out shortcomings with current code recommendations on the subject and recommending corrections). However, it is apparent that his criticisms of force-based design and his proposals for DBD were truly appear groundbreaking.

It is with great sadness that we see the passing of Nigel, who was a good friend and mentor and whose critical thinking and foresight in earthquake engineering lead to major developments in the field and stimulated in many, including myself, a real passion for the subject.

Contributions to Masonry (Katrin Beyer)

Most of us ROSE School students who worked with Nigel Priestley during his time in Pavia knew him mainly as an outstanding scholar in the design of reinforced concrete and prestressed concrete structures and as the inventor of the Direct Displacement-based Design methodology and relatively little did we know of his achievements with regard to the seismic design of masonry structures. Of course, the first of the three text books co-authored by Nigel (Paulay & Priestley, 1992) had "masonry" in the title but by the time we met Nigel he seemed to no longer perform research in this area. When I started studying unreinforced masonry structures after my PhD, I found that most topics I turned to, Nigel had already looked at many years ago when preparing the book with Tom Paulay or in fact relatively recently together with Michele Calvi and Mervyn Kowalsky when writing their DDBD-book (Priestley et al., 2007).

I was always amazed how Nigel managed to capture the essential mechanical behaviour in equations that seem almost too simple but give just as good results as much more sophisticated models. An example of such a result, is the drift capacity equation for URM walls failing in flexure, which – to my knowledge – is the first attempt to develop a mechanical model for the drift capacity of URM walls, which is extremely simple, and yields astonishingly excellent results (Petry and Beyer, 2015).

Reinforced masonry is not one of my research areas but when I attended in May of this year the North American Masonry Conference in Denver, I immediately realised that Nigel had left a significant footprint in this area too: A good part of the papers on reinforced masonry turned around the possibility of confining the toe of the walls and Nigel's confinement plate (Priestley and Bridgeman, 1974) was mentioned more than once. His constitutive model for unconfined and confined concrete masonry is also still widely applied (Priestley and Elder, 1983).

I first met Nigel when I was doing my Master's project with Tom Paulay in Christchurch. He walked into Tom's office and I – awestruck by the fact that I was just meeting the third of the three big P's – did not say much. I tried to do better three years later when I had become a PhD student in Pavia and Nigel was teaching the course "Fundamentals of Seismic Design". It was a unique course because we were given the first drafts of parts of the DDBD-book to read and many of us did course projects on problems Nigel wanted to have confirmed. Though at the time I was certainly not yet in the position to appreciate just how revolutionary DDBD is, I was absolutely excited at seeing for the first time what research could lead to. Having had the opportunity to attend Nigel's courses and to work with him during my PhD was a true gift and I am extremely grateful for it.

Contributions to Analysis (editor)

Nigel Priestley is much better known for his contributions on the Design side of the earthquake engineering Design/Analysis divide. Indeed, as Dr Sullivan has already pointed out in his article, Nigel's major contribution in the development of his new design method, Direct Displacement-Based Design, was in recognising that increasingly complex analysis models gave us very little additional insight into how our structures would be expected to respond when pushed into the nonlinear range.

Those familiar with Nigel's work (particularly in the development of DDBD) will know that his conceptually simple design methods were underpinned by nonlinear response history analysis (NRHA), mostly carried out in Professor Athol Carr's analysis program, Ruaumoko. Many of his MSc and PhD students developed DDBD design equations for different structural systems based on large batch files worth of Ruaumoko analyses.

Nigel was also quite capable of running Ruaumoko himself, however, and it was in carrying out some simple nonlinear analyses that he noticed a discrepancy between the way that viscous damping is modelled in single degree of freedom analyses (as a constant) and how it is often modelled in multiple degree of freedom analyses (varying with the tangent stiffness matrix). Towards the end of my PhD, we wrote a paper together on "Viscous damping in seismic design and analysis" (Priestley and Grant, 2005). In this paper, Nigel reasoned about the role of viscous damping in NRHA, and concluded that a damping matrix based on the tangent stiffness was the most appropriate. He (and his co-authors) subsequently went on to study this conclusion in laboratory tests on bridge piers (Petrini et al., 2008) and analytical studies on reinforced concrete wall buildings (Smyrou et al., 2011). It is interesting to see Nigel's work on damping cited in Andreas Nielsen's paper, later in this newsletter.

In the last decade, performance-based earthquake engineering practice has developed to the point that, at least in some parts of the world, NRHA is routine in checking the design of certain types of structure, such as tall buildings. However, there is a risk that NRHA is used in lieu of a genuine understanding in how the building is likely to perform in an earthquake, rather than to validate the engineer's structural concept. The "deterministic" safety net that capacity design was supposed to offer (although Nigel's work on dynamic amplification in structural wall buildings cast some early doubts: Priestley and Amaris, 2002) has been replaced with "demonstrate no collapse under a (fairly arbitrarily-defined) Maximum Considered Earthquake ground motion".

In his teaching and engineering practice, Nigel recognised the value of detailed structural analysis, but placed more emphasis on the designer's role in determining seismic structural performance, with appropriate allocation of strength and detailing to accommodate this. For those of us who have a tendency to get carried away with computer analysis, this is an important lesson to remember.

Lesser Known Tales (Michele Calvi)

Since you are asking about Nigel's untold stories, or at least not so widely known, I will briefly tell you a few old tales.

One of Nigel's first engineering loves has been masonry. When I first met him in 1987 he was the agent provocateur in the TECCMAR project, aiming to reduce the seismic risk related to masonry buildings in Southern California. Several times I enjoyed listening to sentences which could have been read in literature as the king has no clothes.

However, one of the reasons why his name was well known to me was that a few years earlier, when I was sitting in Vitelmo Bertero class at Berkeley, the number one reference he was recommending was a book edited by Emilio Rosenblueth, titled Design of Earthquake Resistant Structures (Rosenblueth, 1980); Nigel was the author of the chapter on masonry structures. Should one look into the table of contents of this book and see the list of eminent authors of each chapter, it will become apparent that Nigel in his thirties was already a recognized star in earthquake engineering.

In the early 2000's we were working together on the repair and strengthening of the Anatolian Viaduct, which had been shortened of about 1.5 m by the 1999 Duzce earthquake and displaced laterally by as similar distance.

We decided to transform 119 simply supported spans into six continuous decks of about 800 m each.

One of the many problems to be checked and solved was originated by the stresses induced by differential temperature variations in the upper and lower part the deck.

I confess I was surprised to learn that the most viable simple approach to face this problem had been developed and published by Nigel some fifteen years earlier. Nothing to do with earthquakes and seismic design. I quote here from our design report:

"Differential thermal loading, with top surface hotter than soffit will tend to cause the spans to hog upwards. In the current configuration this is unrestrained, but making full continuity over supports will mean that hogging is restrained, inducing tension stress on the soffit. The method of analysis is that developed by Priestley [see ch.5, The Thermal Response of Concrete Bridges in Cope, 1987]."

A last note on the seismic design of tanks and silos.

If one should take the time to compare different codes worldwide on this subject he will be a little surprised of how much they look alike. Much more than for any other area I am familiar with in structural engineering codes.

Do not be surprised: they all are derived from the same document – Priestley et al., 1986, "Seismic Design of Storage Tanks".

Just take three contributions and add them to what is well known about Nigel's outstanding career in earthquake engineering and you may have a feeling of a fraction of his genius.

Edmund Booth's Vote of Thanks to Nigel Priestley on the occasion of his Mallet Milne Lecture, London, May 2003 (Priestley, 2003).

It was not until 1996 that I first met Nigel Priestley. Of course I had heard about him as one of the group of New Zealanders – with Powell, Buckle, Fenwick and no doubt others– who had studied with Park & Paulay at Christchurch, and gone on to conquer large parts of the known earthquake engineering universe. Someone that the great Tom Paulay had chosen as co-author for his book on the seismic design of concrete and masonry had to be pretty special, so it was with real anticipation that I went into Nigel's keynote lecture at the Tenth world conference in Acapulco.

But it was also with some scepticism. His subject was displacement based design. People had been talking about this for some years, and claiming it as a new insight that earthquake problems were driven by displacements, not external forces. Well, of course that wasn't in any way a new revelation, and anyway existing design methods were firmly displacement based, since they set maximum deflections as *R* or (in Europe) *q* times the yield deflection. So what was new?

Nigel, in a brilliant lecture, set me right. What was new was the use of non-linear static analysis as a practical design tool for establishing the distribution of plastic strains within a structure during a design event (something that existing elastic methods were intrinsically incapable of doing) and then going on to relate these strains to seismic performance.

I've had the honour and pleasure of meeting Nigel three times since that Acapulco conference, and got to know a bit better his typically New Zealand virtues of rigorous, independent thinking, a very practical down to earth approach and – yes – old fashioned personal charm. So when I heard that he had agreed to give the ninth Mallet-Milne lecture, I knew that we had a superstar on our hands, a worthy successor to James Jackson who would greatly strengthen our lecture series. And I was delighted to be asked to give the vote thanks, because I was sure there would be no difficulty in finding positive things to say.

And so to the lecture itself. Ladies and gentlemen, I can tell you from recent personal experience that radical change is immensely painful, and if we are to take on board the implications of Nigel's lecture, some quite major changes will be necessary in the way we do things. Perhaps least painful may be changing our approach to multi-modal ductility modified response spectrum analysis; yes, we were slightly in love with it, but knew on what shaky foundations it was based. Nigel has shown us that there are practical ways forward here, though tantalizingly it seems we are going to have to wait a bit longer before he presents us with a universal solution. Relating concrete stiffness to strength will involve a greater change in mindset. Priestley's equation "normalised yield curvature equals Priestley's number P" is easy to remember, particularly since P is (it seems) more or less always equal to two. Can it really be that simple? Yet having to set member strengths before carrying out our analyses is going to be hard. Harder still will be the idea that full, buxom hysteretic loops – which I think Nigel's mentor Tom Paulay taught us to love so much – may actually be less desirable than the curvaceous but anorexic non-linear elastic ones we have been shown in his lecture (and of course since it is Nigel, have been shown how to achieve in practice, too). And then there is the fundamental way in which we carry out displacement based designs. Nigel at the Mallet-Milne dinner last night said that the Americans in their recent codes had got it all wrong, but he was perhaps too polite to mention what we Europeans have done in Eurocode 8. Will we have the courage to change on this side of the Atlantic, I wonder?

Having given us so many challenges, Nigel went on to show us, in a dazzling display at the end of his lecture, some of the surprising and disturbing consequences of sticking to the old ways of doing things. Ladies and Gentlemen, the wise wizard from Middle Earth has spoken. We have all been enthralled and many of us will continue to be enlightened by his words in the years to come.

In Memory of Nigel Priestley (Ian Kirker, on behalf of IPENZ UK Branch, London)

Many of us were privileged to pass through the University of Canterbury when the three P's were at their peak and keeping the Civil Engineering students in check. We remember Nigel Priestley as a man with world expert knowledge, much enthusiasm, vigour and passion for the subject of all matters relating to concrete and seismicity. This knowledge was of course always conveyed in a straight forward although speedy way, presuming a certain degree of intelligence and interest by the students! After graduating and gaining experience in New Zealand, several of us came over to the UK for a few years, and inevitably stayed much longer. Perhaps it was only then, after leaving university, that we all realised how very privileged we had been.

However the contact with NZ seismic experts was not lost, even allowing for Nigel's excursions to California and Italy. When encountering tricky seismic and concrete problems on various projects around the world, Nigel was always receptive to correspondence, phone calls and positively helping our members out with advice, recommendations and generally taking an interest in our progress on these UK shores.

It was a privilege to attend Nigel's talk at the prestigious SECED ninth Mallet-Milne lecture in 2003 at the ICE in London, on the subject of 'Revisiting myths and fallacies in earthquake engineering.' I recollect how Nigel explained that it was always helpful to have a catchy title to get a good sized audience, and then once they were all assembled, to tell them about what you really wanted to lecture, mostly relevant to the title! The lecture of course was a quick rundown on how to analyse and design seismically resistant structures to the latest concepts of forced displacement, and highlighting some potential pitfalls in existing thinking on elastic analysis. Nigel was inevitably the key man in helping to develop and deliver these new concepts at the time to the industry. There was plenty for all of us to think about. Nigel, a luminary in his field, as usual, was years ahead of most of his assembled audience.

We will be for ever grateful for his contribution, guidance and friendship.

Nigel Priestley's role in the Canterbury Earthquakes Royal Commission (Didier Pettinga)

One of the last significant contributions that Nigel Priestley made to the earthquake engineering community of New Zealand, came through his role on the Expert Panel of the Royal Commission that investigated the major building failures that occurred as a result of the Canterbury Earthquake sequence.

The Canterbury Earthquake sequence, that has recently reshaped the earthquake engineering scene in New Zealand, began with a M7.1 event on September 4th 2010 that had its epicentre approximately 40 km away from the Christchurch central city. Many in the global earthquake engineering community are now familiar with the sequence of aftershocks and new events that were to follow over the next 16 months. The most significant of these subsequent earthquakes was the M6.2 February 22nd 2011 event, located 10 km from the city centre. The extremely high recorded ground accelerations, and the focus of damage to land, structures and infrastructure is well documented. It has also been a catalyst to intensified research efforts in all sectors of New Zealand earthquake engineering, and has seen the up-take of new or high-performance building technologies in many of the re-development projects. Many of these steps forward derive from Nigel's research and teaching efforts over the past two decades.

Nigel had his first step in to academia at the University of Canterbury, in Christchurch. Following his time spent at UC San Diego and the ROSE School in Pavia, he had settled back in Christchurch. While he was not heavily involved in the activities of the structural group at the University of Canterbury following his return, his presence as a local expert in building performance, evaluation and analysis was recognised by the request to be part of the Royal Commission.

The Royal Commission was formed to provide a means of cohesively investigating the aftermath of the earthquake sequence. The mandate of the inquiry had two broad aspects, the first to investigate the performance of sample buildings in the Christchurch CBD, and the second to review the adequacy of current legal and best-practice requirements for design, construction and maintenance of buildings in known regions with an earthquake risk. Nigel's role on the Expert Panel that investigated the performance of a number of the buildings in the Central Business District (CBD) of Christchurch, provided some of the key understandings to what had led to the poor structural behaviour observed.

Two building collapses in the Christchurch CBD contributed the majority of fatalities in the February 22nd 2011 event. Nigel was heavily involved in the review of the CTV and Pyne Gould Corporation (PGC) building collapses, and the findings from the post-earthquake inspections following the September 4th 2010 earthquake, and December 26th 2010 aftershocks. While these two buildings represented design and construction from different eras, both buildings had been the subject of structural engineering evaluations prior to the earthquakes and various recommendations and strengthening measures had been proposed and/or enacted in each case. In the case of the PGC building, Nigel provided an extensive discussion that interpreted not only the observed collapse behaviour, but also interrogated the non-linear time history analyses that had been used in both pre- and post-earthquake assessments of the structure. In correlating both the analytical and observation based evidence, Nigel provided a masterclass in understanding building response to earthquakes, starting from first-principles and working right through to the fineries of modern analytical procedures. In my mind, it was this type of wide-ranging knowledge and ability to critically interpret information that made Nigel unique in the modern earthquake engineering field.

As mentioned by other contributors in this issue of the SECED newsletter, the development of the Direct Displacement-Based Design (DDBD) method has opened up a multitude of doors to better understanding the response of structures to earthquake ground motions. For me personally, the opportunity to work with Nigel during a time of intense development of the method continues to provide satisfaction in a range of applications both small and large on a weekly, if not daily, basis. To thus find myself giving evidence as part of the New Building Technologies hearing during the Royal Commission, as a practitioner with experience of using DDBD in practice, was both an honour and opportunity to reflect on its up-take outside of academia. The challenge in putting together the presentation for the Commission was to not simply repeat the advantages already stated by Nigel in his opening presentation on the method, but to set-out and explain where things came unstuck and reverting back to standard practice was inevitable. Knowing that Nigel would have an opportunity to respond to my comments, my main focus became to avoid having the terms "irrational", "irrelevant" or "obviously in error" used in reference to the points I had made!

As many have noted, Nigel's contributions throughout his career have covered a breadth of topics that is both astounding, inspiring and maybe ominous for aspiring structural engineers. It is a rare ability to hold a discussion that seamlessly combines the clarity of first-principle thinking with the understanding of advanced analysis techniques and results. In his contributions to the Royal Commission Nigel exemplified this gift, with the changes now coming through in New Zealand practice holding significant reference to his efforts.

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On Galilean Invariance of Damping Matrices (and What it Means in Practice)

Andreas H. Nielsen
Atkins
Glasgow

Introduction

Of the four terms in the linear equations of equilibrium,

$$\mathbf{M}\ddot{\mathbf{u}} + \mathbf{C}\dot{\mathbf{u}} + \mathbf{K}\mathbf{u} = \mathbf{F} \tag{1}$$

the second term, which provides a viscous damping force, is the most obscure. The first term derives directly from Newton's second law of motion and represents inertial resistance (it is easier to accelerate an empty wheelbarrow than a full one). The third term derives from Hooke's law and describes simple proportionality between applied force and extension (something that should be familiar to anyone who has grappled with a chest expander). The $\mathbf{F}$ term on the right hand side represents external forces applied to the system (the feeling of force transferred through one's hands and into arms and shoulders). However, the damping term remains vaguely unfamiliar. On engineering sketches, we use the symbol of a dashpot, and maybe we can get some sense of the effect from a simple bicycle pump. The dashpot suggests a mental image of a fluid being compressed and forced to flow through a narrow orifice, but how does the response of a fluid relate to the physical reality of damping in structural solids and geological materials?

The first and most obvious answer is that it doesn't. In many cases, viscous damping is simply a convenient model for a range of natural processes, which are not necessarily viscous; convenient, because this model preserves the linearity of the governing differential equations. Apart from a few instances of genuinely viscous forces in nature, such as drag forces and dashpots developed for industrial applications, the dissipation of energy is caused by non-conservative forces that are not viscous. However, the effect of damping is small or beneficial in many practical applications and so, within the range of engineering precision, it is considered valid to approximate the dissipative internal forces by a viscous term.

This article is intended to shed to some light on one particular problem related to damping in seismic analysis and concerns the use of Rayleigh damping, which is a popular type of viscous damping. The article builds on a previous paper [1] and offers some fresh perspectives on the problem.

Using Rayleigh damping for seismic analysis

A brief literature study reveals that a number of methods are available for modelling of damping in time-domain analysis (e.g. [2], [3] & [4]). Viscous damping is routinely assumed, and a certain variant of viscous damping called Rayleigh damping is a popular choice, not least because most commercial finite element (FE) codes offer no alternatives for direct integration procedures. In this method, the damping matrix C is defined as a combination of the mass and stiffness matrices, M and K, such that

$$\mathbf{C} = \alpha\mathbf{M} + \beta\mathbf{K} \tag{2}$$

where α and β are real scalars.

It is generally acknowledged that there is little physical evidence to support Rayleigh damping. The method gives damping levels that are dependent on frequency, although many real systems display hysteretic damping, which is largely independent of frequency. On a more fundamental level, it can be shown [1] that the mass-proportional damping matrix $\alpha\mathbf{M}$ does not remain invariant under a Galilean transformation, as it must do to comply with laws of physics. Simply speaking, Galilean invariance means that the response of two identical systems subject to identical forces must be the same even if one is travelling at a constant velocity relative to the other. This would not be the case for two systems with mass-proportional damping as one system would experience more or less of drag force than the other. It follows as a corollary that it is impossible to design or find in nature a system with true mass-proportional damping.

Despite the obvious limitations, it is possible to ascribe some physical meaning to the two terms in Equation (2). For example, when multi-storey structures are considered, $\beta\mathbf{K}$ may be considered to model energy dissipation arising from inter-storey drifts, while $\alpha\mathbf{M}$ is similar to a viscous fluid surrounding the structure. It is not the case, however, that a structure submerged in fluid is a case of true mass-proportional damping: firstly, the forces exerted on the structure by the fluid are external forces (whereas mass-proportional damping is supposed to be an internal effect); secondly, the fluid forces are not proportional to the mass of the structure, but typically to the cross-sectional area times a drag coefficient.

Earthquakes excite a structure through acceleration of the structure's foundation. The fluid interpretation of the $\alpha\mathbf{M}$ term suggests that particular care is needed in this case. One may surmise that the Rayleigh fluid should move with the foundation such that only flexible modes of vibration relative to the base motion are damped. If the fluid did not move with the foundation, any rigid body component of the velocity vector would give rise to a non-zero viscous term in the equations of motion even though a rigid body should not experience any internal damping. This intuitive interpretation, which is closely related to the lack of Galilean invariance, can be justified mathematically [1]. I shall not repeat the derivation here, but merely summarise the results in what follows.

For seismic analysis we have to choose between an inertial frame of reference (a fixed coordinate system) and an accelerated frame of reference (a coordinate system that follows the base motion). In the former case, we take the terms involving the known input motion to the right hand side of the equations and solve for total displacements, $\mathbf{u}$. In the latter case, we apply fictive forces equal to $-\mathbf{M}\ddot{\mathbf{s}}$, where $\ddot{\mathbf{s}}$ is a vector populated with the three components of earthquake acceleration at the base of the structure, and solve for relative displacements, $\mathbf{w} = \mathbf{u} - \mathbf{s}$. Now, for complete equivalence between the two approaches and in order to "mend" the mass-proportional damping matrix's lack of invariance, in the former case only, we have to add a correction term $\mathbf{F}_c$ on the right hand side of the equations of motion. The complete equations of motions in an inertial frame of reference can then be written as:

$$\mathbf{M}_{aa}\ddot{\mathbf{u}}_a + \mathbf{C}_{aa}\dot{\mathbf{u}}_a + \mathbf{K}_{aa}\mathbf{u}_a = -\left(\mathbf{M}_{ab}\ddot{\mathbf{s}}_b + \mathbf{C}_{ab}\dot{\mathbf{s}}_b + \mathbf{K}_{ab}\mathbf{s}_b\right) + \mathbf{F}_c \tag{3}$$

where $\mathbf{C}$ is given by Equation (2) and indices a and b indicate submatrices (or -vectors) and refer to the superstructure and the foundation, respectively. The aforementioned correction term, which ensures that the Rayleigh fluid moves with the foundation, is given by:

$$\mathbf{F}_c = \alpha\left(\mathbf{M}_{aa}\dot{\mathbf{s}}_a + \mathbf{M}_{ab}\dot{\mathbf{s}}_b\right) \quad . \tag{4}$$

Unfortunately, this term is not commonly recognised. Most, if not all, commercial FE codes do not include the term. The solution is either to apply $\mathbf{F}_c$ manually as a body force to the structure or to conduct the analysis in an accelerated frame of reference, in which the commonly recognised equations of motion are unchanged:

$$\mathbf{M}_{aa}\ddot{\mathbf{w}}_a + \mathbf{C}_{aa}\dot{\mathbf{w}}_a + \mathbf{K}_{aa}\mathbf{w}_a = -\mathbf{M}_{aa}\ddot{\mathbf{s}}_a \quad . \tag{5}$$

It should be emphasised that Equations (3) and (5) yield the same load effects, but only if the term $\mathbf{F}_c$ is included in Equation (3); otherwise, they differ.

Examples and recommendations

As mentioned previously, most, if not all, FE codes do not include the correction term given by Equation (4) in Equation (3). Different results are therefore obtained depending on the chosen frame of reference. Some examples were provided in [1].

In one example, analysed in ANSYS, the mass-proportional damping term was found to cause sliding of a rigid block supported on a fictional interface when analysed in an inertial frame of reference, but no sliding occurred when the same model was analysed in an accelerated frame of reference. The physics of the problem dictated that no sliding occur at all.

In another example, a cantilever excited by sinusoidal base motion at a frequency equal to half of the natural frequency of the cantilever was analysed: firstly in an inertial frame, and secondly in an accelerated frame. The two analyses gave remarkably different results. However, it was easy to obtain identical results by specifying the correction term $\mathbf{F}_c$ defined in Equation (4) as an externally applied force in the inertial frame analysis.

Finally, in [1], I concluded that for an arbitrary linear system the difference between an inertial frame analysis without the correction term and an accelerated frame analysis would be most pronounced when the system is excited by narrow band excitation at frequencies below the first natural frequency of the system; whereas for a system subject to broadband excitation covering a range of frequencies at, or above, the first natural frequency, the difference would be small and typically within the precision required for engineering calculations.

The design motions in earthquake engineering tend to be of broadband nature. The mass coefficient α is often chosen such that the damping is at the right level (typically 4–7%) at the lowest frequency of interest (either the first natural frequency or the first significant frequency in the input motion). When α is determined in this manner, the effect of mass-proportional damping is not particularly pronounced, and the error of using Equation (3) without the correction term should be acceptable – at least for a linear system.

It is difficult to make any predictions for a non-linear system, and particular caution should be exercised in this case. Priestley and Grant [5] argue that the tangent stiffness be used to determine the elastic damping coefficients, and that the damping matrix be updated accordingly during the analysis. However, most FE codes calculate $\beta\mathbf{K}$ from the initial stiffness and provide no option for updating the damping matrix during the analysis. Even if it were possible to update $\beta\mathbf{K}$, the resulting damping ratio would not change much at lower frequencies owing to the constant $\alpha\mathbf{M}$ term. Inelastic response in the form of yielding and sliding reduces the effective frequencies of a structure and increase dissipation of energy; at the same time, the effect of the mass-proportional damping becomes more dominant, which is not realistic. In the limit, as rigid body (zero frequency) modes form, mass-proportional damping ceases to be an appropriate damping model, regardless of the chosen frame of reference.

When commercial FE codes are employed, the safe approach for both linear and non-linear systems is to adopt an accelerated frame of reference for the analysis. An accelerated frame may be slightly more cumbersome choice than an inertial frame when the base motion is given as a displacement time history, but otherwise there should be no additional effort associated with an accelerated frame. An accelerated frame is the only choice for mode-based dynamic analysis and provides an opportunity to select a unique damping ratio for each mode, thus avoiding Rayleigh damping altogether.

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Notable Earthquakes March 2014 – June 2014

Reported by British Geological Survey

Issued by: Davie Galloway, British Geological Survey, February 2015.
Non British Earthquake Data supplied by The United States Geological Survey.

			Time			Dep	Magnitude			
Year	Day	Mon	UTC	Lat	Lon	km	ML	Mb	Mw	Location
2014	01	MAR	13:58	56.85N	7.51E	10	3.2			EASTERN NORTH SEA
2014	02	MAR	20:11	27.43N	127.37E	119			6.5	RYUKYU ISLANDS, JAPAN
2014	03	MAR	17:50	53.21N	1.04W	1	1.6			NEW OLLERTON, NOTTS
Felt New Ollerton (3 EMS).										
2014	10	MAR	02:21	53.21N	1.02W	1	1.8			NEW OLLERTON, NOTTS
Felt New Ollerton (3 EMS).										
2014	10	MAR	05:18	40.83N	125.13W	17			6.8	NORTHERN CALIFORNIA
2014	11	MAR	11:37	53.21N	1.02W	1	1.8			NEW OLLERTON, NOTTS
Felt New Ollerton (3 EMS).										
2014	16	MAR	21:16	19.98S	70.70W	20			6.7	TARAPACA, CHILE
2014	18	MAR	20:45	52.32N	6.30W	9	2.2			COUNTY WEXFORD, IRELAND
Felt County Wexford (3 EMS).										
2014	19	MAR	19:34	53.20N	1.02W	1	1.8			NEW OLLERTON, NOTTS
Felt New Ollerton (3 EMS).										
2014	21	MAR	13:45	53.22N	1.02W	1	1.6			NEW OLLERTON, NOTTS
Felt New Ollerton (3 EMS).										
2014	23	MAR	11:46	53.21N	1.02W	1	1.6			NEW OLLERTON, NOTTS
Felt New Ollerton (3 EMS).										
2014	25	MAR	04:23	53.21N	1.02W	1	1.7			NEW OLLERTON, NOTTS
Felt New Ollerton (3 EMS).										
2014	30	MAR	13:29	53.21N	1.02W	1	1.6			NEW OLLERTON, NOTTS
Felt New Ollerton (3 EMS).										
2014	01	APR	23:46	19.61S	70.77W	25			8.2	TARAPACA, CHILE
Six people killed, scores more injured and at least 2,500 buildings and 150 boats damaged in the Iquique area, Tarapaca. Many landslides and power outages also occurred in the epicentral area. A tsunami was also generated with a maximum wave height of 87cm recorded at Tocopilla, Chile.										
2014	01	APR	23:57	19.89S	70.95W	28			6.9	TARAPACA, CHILE
2014	03	APR	01:58	20.31S	70.58W	24			6.5	TARAPACA, CHILE
2014	03	APR	02:43	20.57S	70.49W	22			7.7	TARAPACA, CHILE
2014	03	APR	06:30	51.72N	2.25W	16	2.3			STROUD, GLOUCESTERSHIRE
Felt Stroud (2 EMS).										
2014	04	APR	22:40	28.17N	103.62E	25		5.4		YUNNAN, CHINA
At least 21 people injured, 75 houses destroyed and 2,700 others damaged in the Yongshan area of Yunnan Province, China.										
2014	11	APR	07:07	6.59S	155.05E	61			7.1	PAPUA NEW GUINEA
One person killed and at least 50 buildings destroyed in the town of Buin on Bougainville Island, PNG.										
2014	11	APR	08:16	6.79S	154.95E	20			6.5	PAPUA NEW GUINEA
2014	11	APR	20:29	11.64N	85.88W	135			6.6	NICARAGUA

Year	Day	Mon	Time UTC	Lat	Lon	Dep km	Magnitude ML	Mb	Mw	Location
2014	12	APR	20:14	11.27S	162.15E	23			7.6	SOLOMON ISLANDS
2014	13	APR	12:36	11.46S	162.05E	39			7.4	SOLOMON ISLANDS
2014	13	APR	13:24	11.13S	162.05E	10			6.6	SOLOMON ISLANDS
2014	15	APR	03:57	53.50S	8.72E	11			6.8	BOUVET ISLAND REGION
2014	17	APR	06:07	52.73N	0.73W	2	3.2			OAKHAM, RUTLAND
Felt throughout Rutland, Leicestershire and surrounding areas (4 EMS).										
2014	18	APR	06:50	52.72N	0.73W	3	3.5			OAKHAM, RUTLAND
Felt throughout Rutland, Leicestershire and surrounding areas (4 EMS).										
2014	18	APR	14:27	17.40N	100.97W	24			7.2	GUERRERO, MEXICO
2014	19	APR	01:04	6.66S	155.09E	29			6.6	PAPUA NEW GUINEA
2014	19	APR	13:28	6.76S	155.02E	43			7.5	PAPUA NEW GUINEA
2014	24	APR	03:10	49.64N	127.73W	10			6.5	VANCOUVER ISLAND, CANADA
2014	28	APR	22:05	52.72N	0.73W	3	1.7			OAKHAM, RUTLAND
Felt Oakham, Cottesmore, Ashwell, Langham and Braunston, Rutland (3 EMS).										
2014	01	MAY	06:36	21.45S	170.36E	106			6.6	VANUATU
2014	02	MAY	18:12	53.19N	1.83E	10	3.4			SOUTHERN NORTH SEA
2014	04	MAY	09:15	24.61S	179.09E	527			6.6	FIJI ISLANDS REGION
2014	05	MAY	11:08	19.66N	99.67E	6			6.1	THAILAND
One person killed and 32 others injured in Chiang Rai, Thailand.										
2014	12	MAY	18:38	49.94S	114.80W	11			6.5	SOUTH PACIFIC OCEAN
2014	13	MAY	06:35	7.21N	82.31W	10			6.5	PANAMA
2014	24	MAY	09:25	40.29N	25.39E	6			6.9	AEGEAN SEA
At least 100 people injured on the island of Gokceada, Turkey.										
2014	14	JUN	11:10	10.12S	91.09E	4			6.5	SOUTH INDIAN OCEAN
2014	18	JUN	08:44	53.40N	1.38W	4	2.8			ROTHERHAM, S YORKSHIRE
Felt Rotherham, Sheffield and Doncaster (3 EMS).										
2014	20	JUN	16:01	55.79N	6.35W	6	1.7			ISLAY, ARGYLL & BUTE
Felt Bowmore, Bruichladdich, Ballygrant, Bridgend, Glenegedale and Portnahaven, Islay (3 EMS).										
2014	20	JUN	16:01	55.79N	6.38W	7	2.5			ISLAY, ARGYLL & BUTE
Felt Bowmore, Bruichladdich, Ballygrant, Bridgend, Glenegedale and Portnahaven, Islay (3 EMS)										
2014	23	JUN	19:19	29.98S	177.73W	20			6.9	KERMADEC ISLANDS
2014	23	JUN	19:21	29.94S	177.52W	10			6.5	KERMADEC ISLANDS
2014	23	JUN	20:06	29.94S	177.61W	26			6.7	KERMADEC ISLANDS
2014	23	JUN	20:53	51.85N	178.74E	110			7.9	ALEUTIAN ISLANDS
2014	29	JUN	07:52	55.47S	28.37W	8			6.9	SOUTH SANDWICH ISLANDS
2014	29	JUN	17:15	14.98S	175.51W	18			6.7	TONGA REGION

SECED Newsletter

The SECED Newsletter is published quarterly. All contributions of relevance to the members of the Society are welcome. Manuscripts should be sent by email. Diagrams, pictures and text should be attached in separate electronic files. Hand-drawn diagrams should be scanned in high resolution so as to be suitable for digital reproduction. Photographs should likewise be submitted in high resolution. Colour images are welcome.

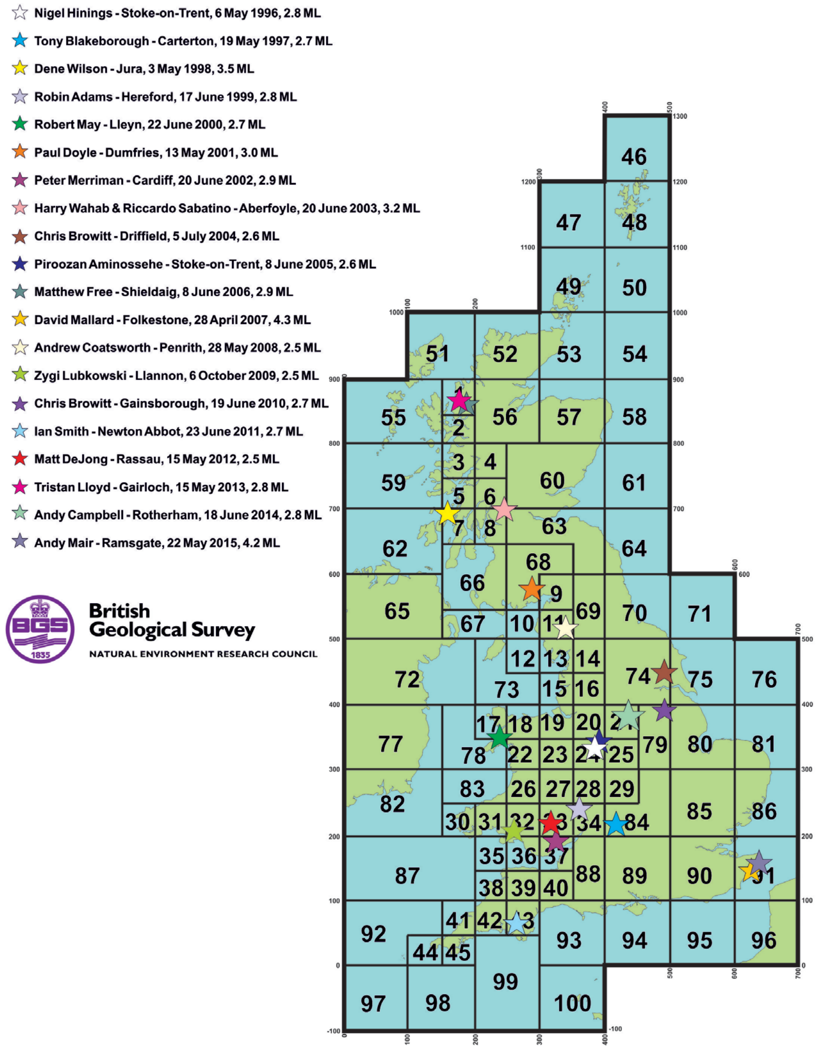
Please contact the Editor of the Newsletter, Damian Grant, for further details: damian.grant@arup.com.

SECED Earthquake Competition Result 2015

When the M_L 4.2 earthquake struck in Ramsgate, Kent, in May last year, Andy Mair, former SECED committee chairperson, became 2015's Earthquake Competition winner. Andy was presented with a bottle of bubbly at October's meeting.

Each year, Alice Walker organises the competition to "predict" the location of the next magnitude 2.5 or greater earthquake to occur in Britain. Participants use both knowledge of historical British seismicity and blind luck (heavily weighted towards the latter) to select locations from the grid shown in the figure below.

This was Andy's first win, although there is a long-standing tradition of SECED committee members winning the prize. Last year, Andy Campbell, current SECED chairperson, successfully located the M_L 2.8 Rotherham earthquake.



Earthquake Competition Winners, 1996–2015

SECED

SECED, The Society for Earthquake and Civil Engineering Dynamics, is the UK national section of the International and European Associations for Earthquake Engineering and is an Associated Society of the Institution of Civil Engineers. It is also sponsored by the Institution of Mechanical Engineers, the Institution of Structural Engineers, and the Geological Society. The Society is also closely associated with the UK Earthquake Engineering Field Investigation Team. The objective of the Society is to promote co-operation in the advancement of knowledge in the fields of earthquake engineering and civil engineering dynamics including blast, impact and other vibration problems.

For further information please contact the SECED Secretary at the ICE at: secretary@seced.org.uk.