RESILIENCE AND VULNERABILITY TO CLIMATE CHANGE THROUGH THE PRISM OF SOIL-WATER INTERACTIONS: CHALLENGES OF TEMPORAL AND GEOGRAPHICAL SCALES FOR GEOTECHNICAL ENGINEERING

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ABSTRACT

The interaction between water and soil particles lies at the heart of the work of geotechnical and geo-environmental engineers. The water content of the subsurface is an important state variable influencing soil behaviour in relation to strength and stability, hydrologic and chemical insulation, sediment budgets and transport, and support for biological life. The capacity of many soils to maintain high shear strength and withstand loads applied to them without significant deformation, crushing or erosion; their ability to insulate contaminated sites and filter heavy metals and organic chemicals out of polluted water; and their effectiveness in supporting healthy biological life for food production and other ecosystem services, are all examples of vital, and sometimes conflicting services, that soils provide and which are critically dependent on water content.

Three major sources of ecological and social change are reasonably certain in the 21st century:

a) increased urbanisation with more demands placed on subsurface systems and structures, by the energy, transport, mining and environmental sectors;
b) increased frequencies, magnitude and duration of droughts and floods as a result of anthropogenic climate change, with likely changes to patterns of precipitation and water retention; and
c) significant rise in sea levels as a result of thermal expansion and melting of glaciers, leading to higher risks of erosion of coastal land and weakening of coastal foundations with possible damage to private properties and critical water, wastewater, telecommunications and transport infrastructure.

The paper‘s goal is threefold. First, different pathways for the impacts of climate change on subsurface systems are described through the lens of soil-water and land-ocean interactions. Second, a case study from Callala beach in Shoalhaven is presented to illustrate the complexity of making adaptation choices at the interface between land and water, especially as a result of uncertainty and unusual temporal and geographical scales of the problems. Third, the readiness of geotechnical education and practice to deal with these problems is discussed in the context of the difference between risk and vulnerability and the emerging distinction between incremental and transformational adaptation. The paper calls on the geotechnical community to engage more fully in the debate on adaptation to climate futures, going beyond the technical assessment of the integrity of infrastructure systems, and identifying long-term strategies for the conflicting demands we place on the subsurface. This will require innovations and possibly some extension of the spatial and temporal scopes of our experimental, analytical and theoretical methodologies.

1 INTRODUCTION

In 1925, Austrian engineer Karl von Terzaghi proposed the concept of effective stress, ultimately linking the strength and deformation of soil to the way the burden of applied load is shared between soil particles and pore water. Since then, the science of soil mechanics has come a long way, developing fully functioning theories of soil behaviour—including Maurice Biot‘s poro-mechanics—with their associated experimental and analytical tools and protocols. As a result, we are now able to account for a large number of observed soil phenomena and use that knowledge in geotechnical design and construction. It was clear from early on that, in almost every geotechnical endeavour, the proportion of water relative to soil minerals in a soil sample—known as either gravimetric or volumetric water content, depending on how it is measured—is a key parameter that has significant bearing on the shear strength of soil, its deformability as well as its ability to conduct liquids, chemicals, heat and electricity. For example, in unsaturated soil mechanics, water content strongly influences the way soil particles are held together by capillary menisci and the extent to which soil water is free to move or become bonded to the surface of soil grains (Fredlund et al., 2012). As a result, water content plays a critical role in such problems as soil compaction, slope stability and landslides, foundation settlement, road pavement design and failures, and low-conductivity clay for waste repositories.

Water content itself is the outcome of environmental and engineering variables that can change in space and time, in the short- and longer terms. Indeed, the most important factors affecting the quantity and physico-chemical state of water in soil are rainfall, runoff, temperature-dependent rates of evaporation and transpiration, water table levels, soil water retention properties, soil hydraulic conductivity and structure and type of soil. All but the last (type of soil) are likely to be affected, at least to some extent, by climate change. Over the last century, a 19 cm rise in global sea levels has been recorded and changes to patterns of precipitation and frequencies of extreme weather events have occurred and are projected to continue, and possibly accelerate, over the course of the 21st century (IPCC, 2013). While the rate and pace of change will depend on scenarios of greenhouse gas emissions, an increase of 2°C in global average temperatures and a 30cm rise in sea levels by 2100 now appear inevitable, with some possibility of larger changes (IPCC, 2013).

Climate change can impact, and be affected by, the work of geotechnical engineers in two major ways. First, the production and distribution of energy is a central focus of the emerging global effort to wean society off GHG-intensive modes of living and economic production and growth. Mining for lower greenhouse gas intensive sources of energy such as natural gas, extracting and distributing renewable energy from geothermal sources or waste bioreactors, and geo-sequestrating carbon dioxide emitted by coal-burning power-plants are examples of three areas of climate change mitigation in which geotechnical engineers have a central contribution to make (e.g., Fragaszy et al., 2011; Basu et al., 2013). Second, natural and engineered subsurface systems (including infrastructure components in the transport, housing, telecommunication, electricity, water and wastewater sectors) can be impacted by changes in key climatic indicators and extreme weather events (e.g., Yasuhara et al., 2012). For example, the integrity of railway and road systems, water and wastewater pipelines, as well as foundations of houses and buildings are likely to be affected by projected changes in rainfall, temperature and sea levels—including associated events such as heatwaves, droughts, flash floods, cyclones and storm surges. With cities in Australia historically developing as port towns and more than 80% of Australians living along the coast today, the effects of sea level rise in particular are expected to be important (Cechet et al., 2011). Furthermore, climate change should be viewed in the context of continuing urbanisation in Australia and overseas, and more demands placed on subsurface systems and structures (State of Australian Cities 2013a; State of Australian Cities 2013b).

This paper is concerned with the second of these connections, i.e., the vulnerability of sub-surface systems to changes in climate. It has three objectives. First, different pathways for the impacts of climate change on geotechnical systems are described through the lens of soil-water and land-ocean interactions. Second, a case study from Callala beach in Shoalhaven is presented to illustrate the complexity of geotechnical and coastal adaptation problems, emanating from their unusual temporal and geographical scales. Finally, the readiness of geotechnical education and practice to deal with these problems is discussed in the context of the emerging distinction between incremental and transformational adaptation.

2 WATER CONTENT, INFRASTRUCTURE AND CLIMATE CHANGE

Climate change may impact subsurface systems[1] in at least three different ways, shown in Figure 1. Pathway 1 refers to the direct impact of a single extreme weather event. For example, a flash flood can alter soil hydro-mechanical properties, decrease suction and strength and temporarily raise the water table. This can cause slope instability (e.g., Briggs, 2010; Yellishetty and Darlington, 2011) or a temporary rise of water table increasing the risk of soil liquefaction (e.g., Take et al., 2014) and/or dissolution of contaminants stored near or below the surface (e.g., Stadler et al., 2012). Under pathways 2 and 3, on the other hand, long-term changes in climatic variables and repeated occurrences of extreme weather events, respectively, may lead to changes in key soil characteristics and consequently failures of engineered or natural subsurface systems. Examples of pathway 2 are the reduction in average precipitation and infiltration and increase in average temperatures and rates of evaporation which may result in a gradual, long-term decline in water table levels and soil water contents and, therefore, seawater intrusion and soil deformation (e.g., Comegna et al., 2012). An instance of pathway 3 is a repetitive occurrence of storm surges over a number of years eroding beach dunes and weakening foundations of foreshore properties (e.g., Suanez et al., 2012; Li et al., 2014). Another example is repeated flash flood events and pore pressure oscillations which may lead to the ―softening" of

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[1] By ―subsurface systems" I mean that part of the lithosphere that is directly relevant to the work of geotechnical and geoenvironmental engineers; they include engineered foundation and underground systems, as well as engineered and non-engineered plant cover, topsoil, aquitards and aquifers; this definition does *not* include deeper geological formations and the earth crust which, with the exception of the effects tectonic-plate movements and earthquakes, are much less relevant to geotechnical engineering. For a review of the effects of climate on the deeper geosphere, the reader is referred to Liggins et al. (2010).

plastic clay, with corresponding loss of strength and progressive failure (e.g., Fan et al., 2014). In many instances, the three pathways may be active simultaneously (e.g., an extreme event triggering slope failure along pathway 1, in a soil that has been undergoing long-term change along pathways 2 and 3).

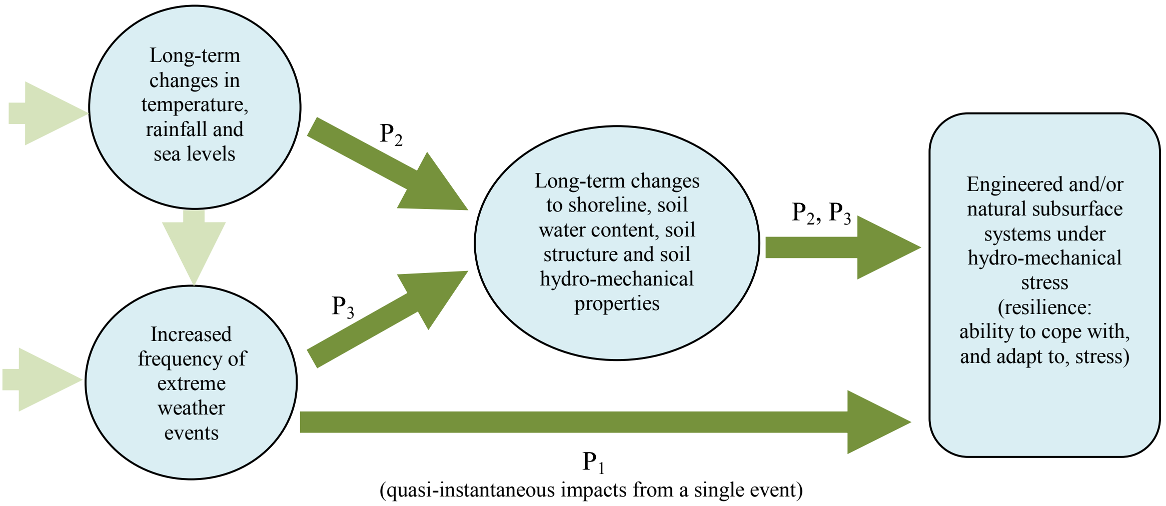

Figure 1. Three pathways (P_1, P_2 and P_3) of impacts of climate change on subsurface systems

Pathway 1 can be analysed and understood by assessing the sensitivity of soil properties and states to key environmental variables, over a time scale of seconds to days or, at most, a season. For example, in many shrink-swell failure problems related to oscillations of suction in the unsaturated zone, the water table is deep and reasonably stable and the pore pressures are hence essentially determined by micro-climate variables, such as rainfall, vegetation and temperature (e.g., Briggs, 2010; Nguyen et al., 2010). It is indeed possible to quantify and manage this sensitivity by means of theoretical, experimental and numerical techniques and tools that are already well-honed in the geotechnical profession.

Studying pathways 2 and 3, on the other hand, raises a number of issues, not least of which is the need to monitor and predict the variability over years and decades of key soil hydro-mechanical variables. Furthermore, given that the principal drivers of the hazards in question are environmental, geographically-widespread (rather than site-specific) risk factors, the above-mentioned variables need to be mapped on large spatial scales of kilometres or more. By contrast, geotechnical and geoenvironmental engineering—like soil science but unlike geography—are disciplines whose methods and theories are premised, by and large, on site-specific information measured on a scale ranging from a few millimetres to a few kilometres.

One soil moisture indicator developed in geography and adopted to some extent in geotechnical engineering is the Thornthwaite Moisture Index (TMI). The TMI measures the balance of soil moisture from rainfall, runoff, evaporation and transpiration and lends itself well to geographical mapping. It has been used for global climate classifications, as an indicator of climate change and for the study of drought, water availability and some aspects of forestry and agriculture (Keim, 2010). Its applications in geotechnical engineering include its use as a proxy for fluctuations in suctions when designing footings or assessing slope stability (e.g., Fityus et al., 1998; Fityus and Buzzi, 2008; Coe, 2012), and road pavement failure (e.g., Austroads, 2004; Philp and Taylor, 2012). Leao (2014) studied the change in TMI in the state of Victoria over 100 years and found a pattern of long-term decline, indicating that a significant proportion of Victorian soils are experiencing long-term drying, consistently with climate change predictions for the state (Climate Change in Victoria, 2008). However, the implications of such trends for the hydro-mechanical behaviour of the subsurface are yet to be elicited. While some studies have attempted to bridge the gap between global climate predictions and specific hazards such as landslides (e.g., Collison et al., 2000; Jomelli et al., 2009; Oku and Nakakita, 2013), there is a dearth of studies about impacts along pathways 2 and 3.

Clearly, such an effort is expensive and would likely require the kind of partnership between industry, research organizations and government that are not readily achievable or easy to sustain. While other geotechnical endeavours in the past have successfully conducted large-scale, multi-party, long-term investigations (e.g., study and design of radioactive waste repositories in Europe and the US), some aspects of adaptation to climate change—especially in relation to temporal and geographical scales, as well as uncertainty—add significant complexity to the problem. These aspects will be illustrated next through a case study of Callala beach in Shoalhaven, south of Sydney.

3 ADAPTATION TO CLIMATE CHANGE: CALLALA BEACH AS A CASE STUDY

Background

Settled coastlines in Australia and overseas have always experienced some morphological and structural change as a result of both natural and man-made processes. However, the magnitude of the projected sea level rise and associated hazards, as well as the relatively small time span over which it is happening—decades rather centuries and millennia—present major challenges to coastal communities and planners. Callala beach is located in Callala bay, along the northern shoreline of Shoalhaven, in the state of New South Wales on the east coast of Australia (see figures 2 and 3). The beach is around five kilometres long, made of quartz sand and characterized by relatively dense development. It is of one eight beaches, identified by the Shoalhaven City Council (SCC) as especially exposed to the effects of sea level rise and associated problems of short- and long-term shoreline erosion, as well as single-event and repeated storm surges and flooding (Adamantidis and Glatz, 2009; Nicholls, 2011; Tonmoy et al., 2012; Royal Haskoning DHV, 2013). In other words, the subsurface at Callala beach and surroundings is set to experience impacts along all 3 pathways shown in Figure 1. Over the next 50 to 100 years, the beach is at high risk of loss of beach width and dunes. The erosion demand (based on extreme storms that occurred in 1974 and 1978) is estimated at 120 m^3/m and the long-term recession rate is 0.05m/year (Adamantidis and Glatz, 2009). Storm-surge erosion is believed to be more significant than long-term erosion. Although, risks of slope instability at bluffs and headlands are present at a number of locations in Shoalhaven, they do not seem to be an issue at Callala beach (Rheinberger & Malorey, 2008).

Figure 2. Location and map of Callala beach in the Shoalhaven region south of Sydney (from Google Earth)

Figure 3. Callala beach after a period of heavy rainfall; close-up photo shows erosion of sand dunes (photos taken by author on 9 September 2014)

Properties at or close to the beach—private dwellings as well as a publicly-owned community centre and public roads—are exposed to the risk of weakening of foundation, submersion and damage from storm surges. Estimated cost of private properties under threat by 2050 is A$150 million in today‘s monetary value. The total value of public infrastructure at risk by 2050—roads and the community centre—is A$230,000 in today‘s values, which grows to $1.1million if risk by 2100 is considered. These forecasts are based on a rise in sea levels, relative to 1990, of 40cm and 90cm, by 2050 and 2100, respectively, which is the best technical advice provided by the New South Wales government to the SCC (Umwelt, 2012). On the positive side, a number of adaptation options, shown in table 1, are available and generally fall under one of three well-known categories of responses, namely protection, accommodation and evacuation/retreat (Nicholls, 2011; Yasuhara et al., 2012). The SCC is currently considering some of these options in consultation with the community and no decision has yet been made.

Table 1. Examples of adaptation options for Callala beach including some of their advantages and drawbacks

Option[1]	**Likely Advantages**	**Some Drawbacks**
Revetment seawalls	Protects properties	Negative impact on beach width; visual impact
Revetment seawalls with a degree beach nourishment	Protects properties	Visual impact; financially costly
Breakwaters	Protects properties	Effect on shoreline and beach width; visual impact; financially costly
Beach nourishment	Protects properties and beach	Costly to public funds; impact on source of sand
Beach nourishment with groyne	Protects properties and beach	Financially costly; impact on source of sand; visual impact
Shoreline stabilisation	Protects properties and beach	Not effective in the long-term; visual impact
Acquisition of private assets by the SCC; compulsory and publicly funded	Eliminates exposure	Financially costly; moral hazard[2]; breakup of community
Voluntary relocation of assets and community; publicly funded	Eliminates exposure	Breakup of community
Rezoning and staged retreat; compulsory and funded by property owners	Eliminates exposure	Financially costly; impacts on community; costly to owners
Managing risk through information and emergency temporary evacuation plans	No engineering cost incurred; flexibility kept for future options	Risk to communities and the SCC

1: options shown are partly based on Royal Haskoning DHV (2013) and reflect the opinion of the author, not necessarily those of the SCC or the Callala beach community; 2: refers to the SCC acting as an insurer of last resort which would encourage risk-taking behaviour.

The question is how best to make a choice between these options, a combination of them (or indeed others that might be added to the list)? It is possible, in theory, to design for a scenario combining worst-case storm surges, long-term erosion and sea level rise. Cost-effectiveness or cost-benefit analyses could be conducted to help in choosing between a number of solutions, aiming to minimize the risk to individuals, properties and public infrastructures, as well as maintain the ecological integrity and amenity of the beach. In other words, the problem can be approached through multi-criteria or multi-objective decision analysis methods. However, the application of conventional decision-making approaches is rendered difficult by a number of elements which add unusual complexity to the issues considered, not least the uncertainty of impacts and the temporal and geographical scales of the problem. These are discussed next.

Multiple Uncertainties and Expanded Range of Solutions

Based on future predictions of Global Circulation Models (GCMs) and past records of sea level rise (over the last few decades), the risks faced by Callala beach are highly significant but the probabilities of their magnitude (as well as those of associated processes of short- and long-term erosion and storm surges) are very difficult to establish. This is because of the multiple chain of causality between, on the one hand, global socio-economic greenhouse gas emission scenarios and, on the other hand, regional and local impacts of climate change—all of which add different levels and types of uncertainty to future predictions. A detailed discussion of the various sources of uncertainty is beyond the scope of this paper and the reader is referred to Smith and Stern (2011) for an excellent discussion of the topic. However, despite the uncertainty, the relationships between global sea level rise and the risks faced by Callala beach are generally monotonic, i.e., higher sea levels always indicate higher risks and there is no uncertainty about the *direction* of the impacts (unlike, for example, hazards associated in many instances with increased or decreased rainfall).

There is a need to consider a range of solutions (as shown in table 1) that are based on technological protection (e.g., seawalls, groynes), ecological modification (e.g., beach nourishment, shoreline stabilisation) and social and institutional behaviour (e.g., relocation, setting up of emergency systems)—all within the same analytical framework that would allow us to make comparisons between them. This range of solutions is broader than the ones normally encountered in engineering projects and requires rigorous integration of community consultation into the different stages of decision-making, since it is difficult in this case to separate the technological and social elements of the interventions considered (El-Zein and Hedemann, 2013; El-Zein, 2014). Choosing between protection, accommodation and retreat is clearly not just a matter of objective management of physical risk because some options can have a significant impacts on the livelihoods of the community. Therefore, scientific and engineering information, as well as choices, values and norms of the community (including the importance of Callala beach itself in the life of the community living close to it) will need to be considered in any adaptation process. For example, the community of Currarong beach—a 15 min drive from Callala bay and experiencing severe erosion problems—expressed a clear preference for beach nourishment when presented with a number of options (Currarong Progress Association, 2013). Likewise it is expected that seawalls and their visual impacts on the beach would face with some opposition within the Callala beach community. Indeed, different interventions might prove to be more suitable depending on whether priority is given to maintaining beach width for recreational, touristic and surfing purposes or achieving cost-effective protection to houses and their foundations. Whether one or the other is preferred is not just a question of scientific merit, but a matter of social choice, politics and values.

For all these reasons (i.e., uncertainty in magnitude of future impacts with no probabilities available, expanded range of solutions and importance of social values and norms in the decision-making process), it is difficult to apply conventional cost-benefit analyses as a decision-making tool. The difference in focus of the different interventions and the fact that at least some of the decision criteria will not be reducible to monetary values will require the deployment of other methods from decision science (e.g., Preston et al., 2013; Kontogianni et al., 2014; El-Zein and Tonmoy, 2015).

Temporal Scale

Two choices related to time, not usually encountered in geotechnical engineering, need to be made in the case of climate adaptation action in Callala beach (and generally coastal adaptation problems).

First, gradual sea-level rise is projected to continue into the next century and the hazard against which protection is required is likely to *worsen* over time. Hence, the choice of time horizon in the analysis and design of the different engineering adaptation options acquires additional importance: it indicates the extent to which possible changes in environmental and/or social conditions affecting the use of the development under consideration are to be incorporated. For example, shoreline stabilisation might be the most cost-effective solution if the time horizon is chosen to be a decade or two, or if sea levels were no longer increasing (Preston et al., 2013). However, it is unlikely to work in the longer term and may even prove counterproductive by conveying a false sense of safety to individuals and communities making long-term decisions about their assets. Hence, a choice of time horizon is no longer just a reference to internal changes to the built structure affecting its performance—as is usually the case in engineering projects—but changes in the social and environmental conditions of its deployment as well. Figure 4 shows the different zones of reduced foundation capacity (ZRFC) prevailing in 2025, 2050 and 2100 and shows that the area at risk will be expanding. Implicit in the choice of the time horizon is a question of intergenerational equity: how much of the cost of adaptation should we choose to pass on to future generations (i.e., generations who will benefit from, and/or carry the burden of, the development beyond the chosen horizon)?

Another time-related decision that needs to be made, is *when* to initiate any adaptation intervention (Tonmoy and El-Zein, 2012; Preston et al., 2013; Lin et al., 2013). This is essentially a voluntary choice and entirely different to the unavoidable lead time required to initiate and execute any engineering project. Intervention time can be designed, in principle, to optimise the outcomes of the intervention. The reason for considering an intervention time other than zero (i.e., other than as soon as possible) is that current arrangements for managing risk might be deemed acceptable, but are not expected to remain so in the future. If, say, a sea wall is found to be the best option for protection against a storm surge under higher sea levels, building one at a given time t in the future (option b) compared to today (benchmark option a), may be more or less desirable. On the negative side for option b are all the lost benefits (i.e., damages) accruing between now and t. These may be significant because of the often irreversible nature of shoreline changes and the possibility of extreme weather events occurring in this period. In addition, there may be added construction difficulties under option b, when sea levels are higher. On the other hand, option b has a few potential advantages over option a. In addition to the financial benefits from a discounted future expenditure, option b leaves the possibility open, between now and t, for the emergence of new technology, as well as some flexibility in case new knowledge becomes available suggesting a different course of action. It is important to keep in mind, however, that option b does not necessarily make the choice of time horizon easier, because there is no guarantee that future projections from time t onwards will be less uncertain than they are now.

Figure 4. Hazard lines for 2025, 2050 and 2100 at Callala beach (adapted from a production by SMEC in Umwelt, 2012; the hazard lines reflect zones of reduced foundation capacity (ZRFC) under conditions of worst storm surge ever recorded and long-term erosional changes occurring between now and the given time horizon; the photo to the right is a zoom-in of the 2050 hazard line and shows position of water and wastewater lines)

Clearly, depending on the choice of time horizon, very different combinations of solutions and intervention times may emerge as optimal at Callala beach. In addition, the uneven distribution of uncertainty in hazard evolution (with near-term projections enjoying a higher level of confidence than longer-term predictions), the robustness of estimates of adaptation benefits may be very different for different time horizons and intervention times. This will make the choice of a course of action undoubtedly more difficult.

Geographical Scale

Is the problem at Callala beach, including its geotechnical elements, a local one? On the one hand, it is possible to give an affirmative answer because:

a) the problem concerns a reasonably well-defined community occupying a surface area of a few kilometre squares in Callala Bay;
b) the engineering solutions being considered are located more or less within that same geographical area;
c) institutionally, the public agency responsible for managing the risks and making adaptation decisions is the local SCC.

On the other hand, three elements of the problem impart on it larger spatial/institutional (i.e., geographical) scales. First, some of the solutions listed in Table 1, such as breakwater, beach nourishment and relocation of the community, may have an impact on localities and systems, beyond the Callala beach area. This is due to the effects on marine ecosystems of breakwaters and beach nourishment (assuming the sand is sourced offshore) and the footprint of the community at destination, in the case of relocation.

Second, it is obvious that the SCC operates within a wider regulatory state and federal coastal management system which places constraints on its actions and can provide direction and resources including funding. For example, the NSW Office of Environment and Heritage has advised the SCC that, as a general rule, protective measures for an individual house can be approved when the erosion escarpment is within 20m of the property in question, an event considered likely today at Callala beach under storm conditions (Royal Haskoning DHV, 2013). The advantage of the rule is that it allows residents some freedom of action in protecting their properties; however, it may also promote mal-adaptation since a large number of protective measures at the level of individual assets is likely to sub-optimal. Hence, unsurprisingly, the wider legal and regulatory framework—over which the local Callala community has little control—can significantly skew the choice of adaptation options.

A third and most important factor is that, given the rise in sea levels and density of settlements along the East Coast of Australia, hazards similar to those faced by Callala Beach and its community are encountered at a large number of beaches along the coast (Kinsela and Hanslow, 2013). This is not, in other words, one isolated problem emanating from the particular characteristics of a particular place. While the question for the Callala beach community is how to protect the Callala beach and adjacent properties, competing priorities can shift the emphasis somewhat for the SCC and other state and federal government agencies, with some level of authority over the beach. For example, decisions about resource allocation must be made and questions about comparative risks in different coastal areas have to be answered before specific action at a specific locality is taken (Preston et al., 2013). From the Shoalhaven City Council perspective, a number of other beaches (e.g., Currarong, Collingwood, Mollymook) are experiencing significant erosional risks too (Adamantidis and Glatz, 2009; Umwelt, 2012; Tonmoy et al., 2012). Implicit in the allocation of resources is a question of intra-generational equity, i.e. which social and environmental priorities should take precedence in public expenditures. In addition, measures of costs and benefits are often scale-dependent (i.e., solutions that are beneficial or ‗cost-effective' at a local scale may not be so at a higher scale) and economies of scale may be achieved when considering problems at larger geographical scales (e.g., Adger et al., 2005; Hallegatte and Corfee-Morlot, 2010; Kontogianni et al., 2014). For example, as indicated earlier in discussing the 20m distance rule, optimal strategies of beach protection or retreat are bound to be different depending on whether they are considered for individual properties or beaches, for the Shoalhaven area or for the state of New South Wales as a whole.

4 RISK, VULNERABILITY AND INCREMENTAL VERSUS TRANSFORMATIONAL ADAPTATION

The rise in sea levels, together with changes to precipitation patterns and increases in the frequencies of extreme weather events, projected to occur within this century, amount to a re-negotiation of long-established boundaries and dynamics of interaction between land and water. How should the risks, unfolding over years and decades rather than weeks and months, be managed and what kind of adaptation will work best? Clearly, the answer depends on specific contexts and specific hazards and on the factors we choose to consider in characterizing the word ―best". However, given the extent of change, interventions that go beyond conventional engineering protective measures may well be required and, as was shown through the case study, the choices we make will depend on the temporal and geographical scales we adopt and the values and norms we prioritize.

A useful distinction here is between risk and vulnerability. If risk is conventionally construed as the likelihood of exposure to the hazard, multiplied by its impacts, the concept of vulnerability incorporates both exposure and impacts and goes beyond them, attempting to account for the differential abilities of individuals, communities, ecosystems, economic sectors and institutions to cope with, and/or adapt to, the hazard in question (e.g., Adger, 2006; Smit and Wandel, 2006; Füssel, 2007; Tonmoy et al., 2014). A shift from *risk* to *vulnerability* in geotechnical engineering would be beneficial in the context of long-term planning for subsurface systems. Such a shift would mark a change of emphasis, moving from the structural integrity and performance of subsurface infrastructure systems to the *services* they provide and the *well-being* of the communities they serve. It would, at the very least, help us avoid narrowly technological perspectives, operate within an expanded range of solutions and better take into account social and institutional factors of adaptations.

Another useful distinction is emerging in the literature between different forms of adaptation. Pelling (2011) defines adaptation as either *resilience*, *transition* or *transformation*. Adaptation as resilience, from this perspective, is the ability to ―support the continuation of desired systems functions into the future through enabling changes in social organisation and the support of technology" (p. 56 of Pelling, 2011). According to Kates et al. (2012), merely *incremental* adaptations are extensions of existing actions or behaviours, whereas *transformational* adaptations are ―those that are adopted at a much larger scale or intensity, those that are truly new to a particular region or resource system, and those that transform places and shift locations." For example, choosing to strategically relocate human settlements from areas of high risk along parts of the Australian coastline as a way of sustainably managing the hazards associated with higher sea levels—should this be considered a sound course of action at a given stage—would require changes in governance, laws, techno-social interactions and ways of thinking about risk management that can be said to amount to a transformational adaptation. Another example is the significant departure from past flood management policies in the Netherlands that are premised on a network of engineering protection systems, replaced by the new so-called ―room-for-the-river" policies which allow, selective and periodic flooding and multi-functional usage of land (e.g., Fliervoet et al., 2013).

An important point here is that resilience and transformational adaptation can sometimes operate *in opposition* to each other, ie the more resilient a system is, the more resistant to transformational adaptation it might be, even when the latter is desirable or essential in the long term (Pelling, 2011). For example, Cooper and Pile (2014) distinguished between adaptation actions that focus on changing human behaviour (e.g., re-settlement; development constraints) from those that aim to change the physical environment in order to minimize impacts on human behaviour (e.g., building defences or nourishing beaches). They argued that the latter is a form of resistance that can delay or prevent adaptation by creating a false belief in technological fixes, whereas the former tends to be a more sustainable response to sea level rise. Conducting a cost-benefit analysis of adaptation options in the eThekwini district in South Africa which includes the city of Durban, Cartwright et al. (2013) found that socio-institutional interventions carried higher benefit-cost ratios than adaptations involving changes to ecosystems or infrastructure systems. On the other hand, there are, and will be in the future, many contexts in which technological adaptation is more sustainable. For example, Koks et al. (2013) studied flood risks in Belgium and found that upgrading defences appears to work generally better than land zoning. However, the point here is that resilience, while often a powerfully positive system property to be reinforced, may be more or less desirable depending on context and scales.

In light of the above discussion, are geotechnical and geo-environmental practice and education well placed to provide sound advice to policy- and decision-makers on issues of long-term adaptation? Clearly, there are no simple answers to the question. However, two points can be made tentatively:

1. The geotechnical profession can draw on strong expertise and well-developed methods and tools to study the sensitivity to extreme events of the hydro-mechanical behaviour of subsurface systems at any given site and, to this extent, it is possible to give an affirmative answer to the question above. There is already a rich body of knowledge on the effects of heavy rainfall and drought on slope stability and the deformation and failure of roads and embankments. We should continue to refine this knowledge and apply it to the management of the risk to infrastructure systems. One of the challenges here is to incorporate in our studies the compound effects of multiple hazards. Two recent examples are the study of the effect of sea level rise in San Francisco on land subsidence, seawater intrusion into groundwater and the inability to drain stormwater and wastewater by gravity (Hanak & Moreno, 2011); and the combined effects of land subsidence and storm surges on levees and seawalls in Shanghai (Wang et al., 2012).

2. Our theoretical and experimental methods and tools for studying long-term changes to subsurface systems are less well developed than they need to be. It is therefore important to incorporate in geotechnical education and practice, far more than we have done so far, the measurement and study of indicators at larger geographical scales—as opposed to site-specific data—in order to be able to make better judgments about long-term adaptation. This would necessarily include stronger reliance on, and better understanding of, Geographical Information Systems (GIS), remote sensing technologies and methods characterising spatial and temporal uncertainty. What geotechnical engineers could then bring to the field is a powerful understanding of subsurface phenomena at multiple scales. For example, geographical studies attempting to develop regional landslide or flooding vulnerability maps tend to make highly simplistic assumptions about failure mechanisms (e.g., Joyce et al., 2014). Geotechnical engineers can clearly enrich these methods by adding a more sophisticated understanding of transport processes and hydro-mechanical failure mechanisms. However, this can only happen if geotechnical education and practice are able and willing to engage with larger geographical scales and longer time frames. Interestingly, Chowdhury and Flentje (2008), examining geo-hazards in the context of growing populations in a globalised world, reached similar conclusions about the importance of multi-disciplinary approaches incorporating methods traditionally more present in the realm of geosciences and geography.

Pursuing these recommendations would place the profession in a better position to play an active role in adaptation to climate change. It would allow geotechnical engineering to provide its input more upstream of the policy-making and planning processes, than is currently the case.

5 CONCLUSIONS

Projected changes to the climate over the next few decades will alter the hydro-mechanical behaviour of many subsurface systems, leading in some cases to higher risk of failure. The sensitivity of key infrastructure systems—such as roads, embankments and slopes—to extreme weather events and fluctuations in soil water content and suction have been assessed in a range of studies in Australia and overseas. However, as shown in this paper, the multiple pathways through which climate can impact subsurface systems, and the unusual temporal and multiple spatial and institutional scales of the problems, add significant complexity to adaptation responses. Our ability as geotechnical engineers to tackle the unprecedented changes likely to be experienced by the subsurface, inland and along the coast, depends on whether we can embrace and/or develop experimental and theoretical tools at different scales to the ones we have mostly worked with so far.

Over the last decade, geomechanics research has made significant advances in developing a better understanding of soil behaviour based on fundamental laws of physics on scales smaller than the representative element volume, from millimetres to micro and nanometres. This research will continue, as it should, and one element of its success lies in the willingness of geotechnical engineering researchers to engage with methods and theories from scientific disciplines that have long-standing experiences with smaller scales, such as physics, chemistry and thermodynamics. Given the changes affecting our planet today, it is now equally important that we extend our interests, and those of our students, towards the larger spatial scales and associated disciplines that will help us better tackle the challenges lying ahead.

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