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| Institution: Imperial College London |
| Unit of Assessment: 14 - Civil and Construction Engineering |
| <p>a. Overview</p> <p>This submission is from Imperial College's Department of Civil and Environmental Engineering. Our research environment has grown in scale and vitality over the REF period, with Cat A staff up from 49.4 to 56.6, a more youthful profile (15 fulltime academic staff under 35 and only six, who are all professors, over 55), average research income up by over 100%, PhDs awarded up by 47% and £12.3m invested in our research facilities.</p> <p>The Department encompasses the full range of civil engineering disciplines through its 5 Sections (listed below), each led by a senior professor.</p> <ul style="list-style-type: none"> • Environmental and Water Resources Engineering (13.6 FTE) covering hydrology, water resources, water/wastewater treatment, urban water systems and waste management; • Fluid mechanics (7.2 FTE) focussing on fluid-structure interactions (especially waves), renewable energy in the marine environment and airflows; • Geotechnics (11.7 FTE) addressing soil behaviour, soil-structure interaction including foundations, tunnels, dams and slopes, geothermal systems and geohazards; • Structures (15.9 FTE) focussing on the built environment, including structural analysis and design, materials, reliability and the management of ageing infrastructure; and • Transport (8.2 FTE) covering travel demand, policy and economics, intelligent systems, geomatics, safety and risk, railway operations and port logistics. |
| <p>b. Research strategy</p> <p>b.1 Vision and research strategy</p> <p>Our RAE2008 objectives were <i>'to deliver world-leading research, to educate some of the world's most capable students to the highest possible level and to provide state-of-the-art advice to industry.'</i> Our vision is to strengthen continuously our world-leading position in civil engineering research and education. Our research strategy is developed by the Head of Department (HoD), Director of Research and Section Heads; its implementation is overseen by the Research Committee. Our current overarching strategy is to:</p> <ol style="list-style-type: none"> i) strive to understand the fundamental processes, materials and structures involved in the built environment and how they interact with society and the natural environment; ii) sustain academic excellence, vitality and critical mass in core areas of civil engineering; iii) extend and deepen multi-disciplinary collaboration to address global challenges; iv) maintain and develop our world-class research facilities; v) recruit excellent research students, regardless of their financial circumstances, and provide them with outstanding training and support; and vi) maximise the impact and societal benefits of our research. <p>b.2 Principal achievements since RAE2008 and future strategic aims</p> <p>b.2.1 Overall</p> <p>Our headline achievements and plans for the next 5 years are summarised below in relation to the strategic aims listed in b.1.</p> <ol style="list-style-type: none"> i) The substantial research outcomes secured over the REF period. These are summarised in b.2.2 to b.2.6, together with the areas that we intend to advance. In future we will give greater emphasis to the sustainable whole life performance of civil engineering infrastructure systems and services including research programmes on multiple use infrastructure, modelling long-term performance, life extension and the circular economy. ii) We have increased our full-time academic staff from 44 to 52, appointing at least 3 new lecturers in each of our 5 sections to: <ol style="list-style-type: none"> a) inject bright, ambitious ECRs with exciting ideas; b) ensure substantial expertise in theoretical and numerical modelling, laboratory experimentation and fieldwork, in every Section; |

- c) provide the critical mass required to allow both problem-driven and curiosity-driven research while also enabling an agile response to emerging opportunities; and
- d) reduce staff teaching and administration to free up more time for research.

We plan to make further strategic academic appointments in: Railways (to better capitalise on opportunities created by our Railways and Transport Strategy Centre (RTSC)), Systems Engineering (to strengthen our research capabilities in building and urban systems) and Environmental Fluid Mechanics to capitalise on our exceptional Hydrodynamics Lab.

- iii) We have played a leading role in developing multi-disciplinary research initiatives focussed on global challenges through College Research Centres, including: *Energy Futures Lab*, *Grantham Institute for Climate Change*, *Centre for Nuclear Engineering*, *Centre for Blast Injury Studies*, *Institute for Security Science and Technology*, *Manufacturing Futures Lab* and *Digital Economy Lab* (see e.1). Since 2010 we have made 5 academic appointments in Energy and others in Climate Change, Sustainable Development and Urban Resilience, each designed to exploit existing capability and foster collaborative research. We plan to establish and develop a College-wide *Urban Systems Lab* (to be directed by *Polak*) and will play a central role in establishing a new College *Institute for the Environment* in 2014.
- iv) We have invested over £12.3m in our research facilities since 2008. Each section has laboratories with state-of-the-art equipment and an excellent environment (see d.1). The construction work for our new Intelligent Infrastructure and Transport Lab has recently been completed and this lab will now be equipped (including the consolidation of £1.6m of existing experimental resources) and commissioned.
- v) The Department has increased the number of full PhD scholarships offered each year from 5 in 2008 to 15 in 2013. These are in great demand from excellent applicants (see c.2). In future, we aim to increase the number available by at least 2 scholarships per year.
- vi) Our research has had substantial economic, social and environmental impact as summarised in REF3a and the associated impact statements. Our impact strategy recognises that many aspects of the construction sector are changing. REF3a details key trends and how we intend to respond to the emerging challenges and opportunities.

b.2.2 Environmental and Water Resources Engineering

Urban water systems and water/wastewater treatment (*N Graham, Keirstead, Maksimovic, Mijic, Stoianov, Templeton*). New methods for urban flood modelling and prediction have been developed, initially supported by an EPSRC Platform Grant in Urban Water. Novel monitoring platforms have been created to capture dynamic hydraulic events in water supply pipe networks (contributing to our ICE 2010 Telford Gold Medal) and these are being applied to study pressure transients and changes in water quality in distribution networks in the NEC funded (£1.7m) Smart Water Lab project (PI: *Stoianov*), complemented by new methods for modelling turbulent flow in pipes. Future work will devise smart water systems with dynamically reconfigurable network topologies for increased resilience and improved pressure/leakage management. Our SynCity modelling framework will be developed and used to examine interactions between urban energy, water and waste systems facilitated by the appointment of *Keirstead* (2011) and *Mijic* (2013). Our work on treatment technologies will be extended to new approaches to neglected water-related diseases in developing countries in collaboration with our Faculty of Medicine.

Hydrology and water resources. (*Butler, Bulygina, Buytaert, McIntyre, Onof, Wheeler*). New tools have been developed for precipitation projections at scales relevant to urban drainage networks and new modelling methods have been devised to support flood risk management. *Buytaert* carried out the first comprehensive assessment of the impact of climate change on the water resources of the tropical Andes and pioneered the implementation of hydrological models as web services as part of a £2m NERC-funded project. Future work will improve rainfall and catchment runoff models and will develop integrated surface water/groundwater resource assessment methods. We aim to develop the next generation of simulation systems (incorporating distributed sensor networks, cloud-based computing and web-services) to underpin sustainable water resources management, facilitated by the appointment of *Bulygina* (2013).

Waste management and resource efficiency (*Cheeseman, Grimes, Smith, Wilson*). *Cheeseman* invented carbon-negative cement based on magnesium silicate which was one of MIT Technology

Review's ten most important emerging technologies for 2010, was a Wall Street Journal Technology Innovation winner and made our Novacem spin out company a World Economic Forum Technology Pioneer (2011). We developed i) microwave pyrolysis for closed-loop rubber recycling; ii) microbial bio-drying technology for the production of solid recovered fuel from municipal solid waste; and iii) a treatment solution for total food waste that is being deployed throughout the UK (>50 installations), Brazil and Hong Kong. Future research will develop a wide range of closed loop methodologies to recover value components from complex waste streams.

b.2.3 Fluid Mechanics (*Alsina, Christou, Heller, Hwang, Spinneken, Sobey, Swan, van Reeuwijk*).

Research on deep water waves has improved understanding of crest height distributions, providing a physical explanation for freak waves and new fully nonlinear 3D wave models. Revised ISO design recommendations for offshore structures require fully-nonlinear wave modelling for wave-in-deck loading and steep wave force calculations. To date, the only fully nonlinear 3D wave models applied in offshore engineering design have originated from our group. Experimental and theoretical work on environmental fluid mechanics has provided new physical insights into the development and break-up of stable stratifications within buildings, the optimal design of natural ventilation systems, the interaction between internal and external building flows and the development of non-Boussinesq plume models. Direct numerical simulations have been used to explain the physics of turbulent entrainment, settling the decade long debate regarding the entrainment law for sheared turbulence in linearly stratified environments.

New appointments have been made to enable future research in strategically important areas. *Spinneken* (2010) is extending our floating structure work for applications to marine renewable devices. *Christou* (2012) will combine laboratory and field data in the study of infra-gravity waves and their impact on LNG offloading operations. *Alsina* (2013) will extend our modelling to sediment transport processes, particularly the prediction of bed shear stresses in the swash zone and *Hwang* (2013) will work in the area of hydrodynamic stability theory, with an emphasis on vortex shedding and vortex-structure interactions.

b.2.4 Geotechnics (*Bommer, Burland, Ghail, Jardine, Kontoe, O'Sullivan, Potts, Saroglou, Sim, Standing, Taborada, Tsiampousi, Zdravkovic*).

Laboratory research. This has advanced with an EPSRC Equipment Grant, a renewed Platform Grant and by appointing *Sim* (2011). EPSRC funded projects include characterising UK mudrocks, particle-scale properties and interface shear, alongside other cyclic loading, unsaturated soil and Africa-focussed studies. Characterising anisotropy and non-linearity by advanced testing has been one major theme (ICE Geotechnical Research Medal 2008), as has substantial facility investment.

Numerical modelling. New aspects of soil behaviour have been captured into ICFEP (our bespoke advanced FE code, supported by Geotechnical Consulting Group, who fund *Potts'* Chair, PhD studentships and facilities) and applied in research, geohazard and major infrastructure studies. Developments since 2008 include: (i) novel deterministic geotechnical risk assessment algorithms (BGA Medal 2012); ii) constitutive models that address ageing/creep when analysing aged infrastructure; iii) more accurate earthquake and cyclic geotechnical simulations (BGA Medal 2008); iv) unsaturated soil developments; v) thermal (THM) modelling and vi) interfacing with ADAPTIC, the Department's structural program in full soil-structure analyses for an EPSRC-funded blinding-strut project. Numerical research involving Discrete Element/Molecular Dynamics approaches has also been highly active and linked to novel laboratory experiments.

Integrated experimental, field and analytical studies. These include a major investigation into how new Crossrail tunnels affect existing tunnels and services (funded by EPSRC £1.1m, Crossrail and Morgan Est) with detailed measurements around new Hyde Park tunnels, novel research with model cast-iron tunnel linings and high quality laboratory element testing. A Joint Industry funded Project has progressed in collaboration with INPG Grenoble into offshore foundations, with intensively instrumented calibration chamber tests and advanced laboratory testing that interface with the French National SOLCYP programme's fieldwork. A (\$1m) BP project (with IC Physics and UPC Barcelona) comprised multi-disciplinary research (from engineering geology to multi-scale thermal modelling) to advance engineering for climate change in cold-regions (Manby Prize 2010).

Future research will build on our new facilities and staff. *Taborada* (appointed 2012) is extending geothermal research with EPSRC (2013) funded temperature-controlled triaxial testing.

Tsiampousi (appointed 2013) will model nuclear waste disposal in conjunction with our Nuclear Engineering Centre. A new Carbon Trust funded project (2013) with DONG Energy, Oxford and UC Dublin will investigate wind-turbine foundations, conducting major field tests and applying our advanced numerical and laboratory capabilities to develop novel design approaches. New research is planned into shale-fracking induced tremors and their effects on structures/services.

b.2.5 Structures

Response to Extreme Loads (Elghazouli, Louca, Stafford). Significant advances have been made on hazard mitigation under earthquake, blast, impact and fire loads. New seismic hazard prediction procedures are already being used in seismic risk assessment for critical structures and nuclear facilities. European and industry sponsored research led to improved seismic design procedures which have been incorporated into Eurocode 8 revisions, and to novel seismic-resistant details. Work with Dstl/MoD, HSE, Office of Naval Research (USA) and industry on improving blast and impact resistance resulted in new policy and design guidance for both civil and defence applications. Research on structural robustness led to the first rational progressive collapse assessment framework actively applied in design practice and incorporated into European and North American design guides. We plan to develop advanced risk assessment procedures for multi-hazard scenarios and to expand our research on extreme loads to a wider range of materials.

Concrete Materials and Structures (Buenfeld, Khoury, Vollum, Wong). Concrete durability research has been supported by our EPSRC Concrete Durability Platform Grant and strengthened by the appointment of *Wong* (2010) and the provision of a new suite of labs; understanding of deterioration processes has been advanced and more effective methods for design and whole life assessment developed. Research on shear behaviour and deflections in concrete slabs led to improved design procedures incorporated into Eurocode 2 and other industry guides. Future research will expand our work on buried and water-resistant concrete structures, environmental performance of concrete materials, applications of fibre and rubber reinforced concrete, and performance assessment of concrete bridges.

Steel and Composite Structures (Camara, Gardner, Hobbs, Malaga, Nethercot, Ruiz-Teran, Wadee). Research on the behaviour of elliptical steel hollow sections, supported by industry and EPSRC, now forms the basis of UK and European design practice and is being incorporated in international codes. Our work on stainless steel led to more accurate and efficient design concepts including the new Continuous Strength Method adopted in Eurocode 3 and North American guides. Research on structural components and assemblages has been underpinned by fundamental work on structural stability leading to improved understanding and new theoretical formulations of interactive buckling problems. Future research will focus on pre-stressed, high-strength and long-span forms as well as hybrid structures that optimise steel use in conjunction with other materials. *Malaga* has been appointed (2013) to develop a new strand of research in timber structures.

Computational Mechanics (Izzuddin, Macorini, Phillips, Sadowski). Novel numerical formulations and procedures for geometric and material nonlinearities were developed and implemented in our in-house finite element program ADAPTIC which is widely applied within the Department and on international collaborations. *Macorini* was appointed (2010) to model masonry structures; a new 3D meso-scale approach is the first to enable accurate representation of both in-plane and out-of-plane masonry panel response. Successful coupling of ADAPTIC with our advanced geotechnical program ICFEP has enabled complex soil-structure modelling. We have extended our computational work into musculoskeletal structures; new approaches developed for bone modelling are now being applied to osteoporosis, prenatal development and blast injuries. A new Centre for Blast Injury Studies with core funding of £5m from The Royal British Legion was established in 2012 in collaboration with Mechanical Engineering, Bioengineering and Medicine. Future research will expand our work on multi-physics, multi-scale and multi-processing structural modelling; there will be a fresh emphasis on shell structures after *Sadowski's* appointment (2013).

b.2.6 Transport

Transport Demand, Economics and Policy (D Graham, Polak, Sivakumar). A new modelling framework linking accessibility with productivity has been developed (DfT/TfL/ESRC-funded), fundamentally reforming UK transport appraisal (e.g. Crossrail and High Speed 2) and assessment of wider economic impacts internationally (e.g. Cross River Rail Brisbane). A new generation of strategic urban systems modelling tools (EPSRC/industry-funded) has been created with decision-

Environment template (REF5)

making across multiple time scales, spatial structures and urban sub-systems including transport, energy and buildings. Future work will extend their scope to control and management.

Geomatics, Air Traffic Management and Safety (Evans, Majumdar, Ochieng, Schuster).

Developments include: i) novel ways of exploiting new GNSS signals to improve the availability of high accuracy positioning for new applications, e.g. aircraft landing (EPSRC and QinetiQ/Astrium); ii) the world's first civil GNSS signal interference monitoring and detection system, GAARDIAN (TSB/£2.2m, led by Chronos); iii) ground-breaking use of 'signals of opportunity' for cost-effective, sub-meter positioning with WiFi-enabled devices, without GNSS (Patent application/1318263.9.); iv) algorithms and tools for GNSS-based aircraft landing and taxiing (Michael Richey Medal 2011), and trajectory prediction for gate-to-gate navigation, both fundamental to the SESAR aviation capacity goal; and v) new non-parametric statistical fatigue analysis method, already implemented by UK CAA in pilot flight time limitation rules. Future work will quantify benefits (e.g. safety) of multiple GNSSs and specify the ATM system beyond 2030 (Eurocontrol-funded).

Urban Mass Transit Operations and Management (D Graham and RTSC). Stochastic frontier analysis methods have been developed for evaluating mass transit operations (rail and bus) with long-term funding (>£6.5m) and data from 70 operators (<http://cometandnova.org>). Research has directly influenced fares policy and approaches to reliability by identifying demand response to changes in fare, income and service. New analysis techniques accounting for KPI interdependencies and normalisation of performance data have been applied to 60 cities; this resulted in improved understanding of relative performance, priority areas, financial savings and influenced policy. Future applications include nascent operators, light-rail and urban road systems.

Intelligent Transport Systems, Logistics and Environment (Angeloudis, Han, Polak). Developments include: i) real time road network management tools underpinned by advanced traffic sensor fusion, traffic state estimation, short term traffic prediction and case based reasoning and already applied by TfL (2012 Olympics); future work will extend to multi-modal networks strengthened by the appointment of *Han* (2013); ii) operational, uncertainty-sensitive algorithms for control of automated guided vehicles and automated cranes; extended to logistics optimisation in nuclear power plant construction (TSB/EPSRC £1.7m with LOR, Arup and BRE); iii) mobile, wireless sensor network technologies and analysis methods to manage congestion and air quality (EPSRC/DfT) with current deployments at Heathrow Airport (NERC) and Glasgow (EU/FP7) to optimise operations. Future work will integrate pollution measurements into exposure assessment, and optimise operations based on real time network performance and ambient environmental data.

c. People

c.1 Staffing strategy and staff development

Ethos. The key factors underpinning our research culture are the quality and drive of our staff. Our priority is to attract and retain highly able, lively and ambitious people who are, or have the potential to become, international research leaders, and then to provide an environment in which they can flourish. Academic appointments are only made to individuals who are believed to have the capability to rise to the level of professor at Imperial.

Recruitment. We strike a balance between appointing to sustain the technical priorities set out in our research strategy and recruiting exceptionally able and lively candidates as they become available across our broad discipline. We actively solicit applications and always continue to search until we find candidates who meet our stringent appointment criteria. We usually have at least 40 applications for each post and shortlisted candidates spend at least a day in the Department where they give an open seminar, engage with potential colleagues, present their research plans and are interviewed. Emphasis has been placed over the past 5 years on recruiting highly promising early career staff who can add to the vitality and sustainability of the Department.

Early career staff. We have appointed 22 ECRs to academic positions since 2008. Start-up packages vary according to needs, but all recent appointees have been provided with a fully funded (fees plus stipend) PhD studentship and a research support fund. Laboratory investment has included significant new facilities and initiatives to support ECRs. ECRs have a reduced teaching load for their first 3 years, typically 30 contact hours in their 1st year and 60 in their 2nd and have no administrative load so that they can focus on research. ECRs undertake 3 years of probation (with a formal mid-term review) and have an academic mentor, usually from outside of

their Section. The College provides ECR training in PhD supervision and research management and we run regular ECR workshops in the Department, for example on building a research group.

Competitively won chairs and fellowships. Two staff held RAEng Research Chairs since 2008: *Fisk* (Sustainable Development) and *Grimes* (Waste Management). Four holders of Marie Curie Fellowships have been appointed as lecturers (*Alsina, Bulygina, Hwang, Macorini*), as have three RCUK Fellows, (*Buytaert, Stafford* and *Stoianov*), and two holding overseas government postdoctoral Fellowships (*Camara and Ruiz Teran*). In addition, five of our recently appointed lecturers have held competitive Government awards to support their PhD studies (*Han, Keirstead, Malaga, Sim and Taborda*). Two professors (*Buenfeld* and *Ochieng*) were elected FREng.

Staff profile and succession. Of our 52 full-time academic staff, 15 are aged under 35, 17 are 35-45, 14 are 45-55 and 6 are over 55. This youthful age profile reflects a highly energetic and sustainable group of academics. In addition we have 10 research active part-time professors (totalling 2.6 FTE) who share their experience with our younger academics. We capitalise on our most capable staff after they retire from full-time positions (e.g. *Burland* and *Nethercot*) by encouraging them to mentor ECRs. Mechanisms include part-time salary payments, continued provision of office and support services, participation in MSc courses, and involvement in seminars and other departmental and sectional events. 12 academic staff have left the Department since 2008. Ten moved to Chairs elsewhere, keeping close on-going relationships with the Department. Despite intense recruitment efforts from other institutions, only two academics have left for other British Universities (*Hunt* to Dyson Chair in Fluid Mechanics at Cambridge and *Mathias*, who was on a fixed term appointment, to Durham). Sadly, another two senior staff (*Pavlovic* and *Ambraseys*) died during the REF period.

Development and promotion. We strive to create the environment and culture that encourages our staff to progress and excel. Most day-to-day academic activities are focussed on, and are supported within, the 5 Sections, whose Heads provide line management and carry out annual appraisals. The latter recognise achievement, identify any points of difficulty and agree targets for the coming year and personal development needs. The College's Learning and Development Centre (<http://www3.imperial.ac.uk/staffdevelopment>) provides management and leadership programmes for all College staff and additional tailored development support for the academic community. Most staff progress effectively. For example, 20 of the 24 academic staff who held non-professorial grades in 2008 have been promoted over the REF period. All of our full-time academic staff aged 54 and over are professors. Eleven of our 13 full-time professors started their academic careers as lecturers in our Department, the youngest (*Gardner*) is only 36.

Financial support. The Department returns overhead income to staff, who are encouraged to build up personal research funds for seed funding new research initiatives and bridge funding for RAs. The Department also covers recruitment and redundancy costs so as to not impact PIs.

Postdocs. Our Department's postdocs are recognised as a community. We are committed to supporting their funding, career development and travel to establish international research contacts. We have a Postdoc Mentor (*Wong*) and two elected postdoc representatives who liaise with academics and the College's Postdoctoral Development Centre (PDC). The Centre offers a tailored programme of support, helping postdocs meet their required 10 days/year of professional development. It also offers personal development in specific skills, career development (including a programme designed specifically for women), coaching and mock interviews. One scheme prepares applicants to compete for Imperial's annual Junior Research Fellowship (JRF) package of salary plus research expenses (for up to 3 years) that enables 20 of the best postdocs to become independent researchers. *Heller* is a Departmental JRF.

Visiting Scholars. Since 2008 we have hosted approximately 60 academic visitors for periods of at least 3 months from leading universities and research institutes in more than 20 countries. Our visitors have often been sponsored by Research Councils, the Royal Society, the RAEng, Charitable Foundations, Commonwealth and Chinese Government Fellowships.

Technical and support staff. The full value of our excellent labs is realised through our strong team of highly skilled, motivated and organized technical staff. We have increased our technician strength to 15 (up from 11.4 in 2008). No technicians have left, except for retirement, since 2008, reflecting the attractive working environment. Our Technical Staff Group identifies future skills needs and maintains and develops our technical provision. It also runs our technician funding and

management structure flexibly between Sections. We have support staff covering research project and research student administration. In addition, each of our Sections has a full-time administrator to unburden academic staff from routine administrative tasks.

International staff. One indicator of our international reach and vitality is that our full-time academic staff originate from 28 countries: Belgium, Bulgaria, Canada, China, Cyprus, Egypt, France, Germany, Greece, Holland, India, Ireland, Italy, Kenya, Lebanon, Malaysia, New Zealand, Palestine, Peru, Poland, Portugal, Serbia, South Korea, Spain, Sri Lanka, Ukraine, UK and US.

Evidence of equality and diversity. The Department supports the College's framework for achieving equality and diversity. Imperial has an Equality and Diversity Unit whose remit includes advice on best practice. The College has systematic, fair and transparent recruitment processes and conducts staff questionnaires to help identify problems (including appropriate follow up procedures). The College's family friendly policies regarding flexible working hours and excellent subsidised on-site nursery have benefitted many staff. Meetings and teaching are scheduled to be compatible with parental duties. We have an institutional Athena SWAN Silver Award and continue to be a Stonewall Diversity Champion. The College resources a range of equality-related networks including Imperial as One (race), Imperial 600 (LGBT) and disability staff and student forums and leadership programmes including iLead (BME) and Calibre (Disability). One notable development, supported by the College's Female Academic Development Centre, has been the sharp increase since 2008 in the number of female staff. Ten of the Department's academics are women including 2 professors (*Grimes and Zdravkovic*). *Kontoe* and *Ruiz-Teran* have taken periods of maternity leave during the REF period and all maternity returners are offered an Elsie Widdowson Fellowship which provides a year of research without teaching or administrative duties.

Intellectual environment. We endeavour to create an intellectual environment in which lively research discussion and collaboration are integral to daily life. Most weeks see at least 3 lectures and/or research seminars in the Department with internationally recognised speakers. Prestigious discipline-specific lectures hosted by the Department include Rankine (geotechnics), Paviers (construction), Lloyd's Register Foundation (safety) and Laing O'Rourke (systems). Our 5 Sections all organise regular research seminars, while more generic events promoting interdisciplinarity and professional breadth, are convened by the Department. These include industry workshops that identify and discuss the latest research needs. Recent examples include workshops involving around 20 senior staff from Arup and Imperial on i) Funding research linked to major construction projects; and ii) Future cities. Meanwhile, the College organises *Grand Challenge Labs* and *Ideas Labs* to identify large scale research opportunities and to seed collaboration between Departments.

Research pervades our taught MSc programme. We graduate 240 MSc students per year (from around 1500 applicants) who all produce a significant research-orientated thesis following 3-5 months of full time research, often working with PhD students and in some cases staying on for a PhD themselves. Their projects test new ideas and incubate proposals for larger projects. They are also used to create new collaborations through joint supervision with industry and academics from other Departments, particularly through shared MSc courses such as the MSc in Sustainable Energy Futures (directed by *Spinneken*).

c.2 Research students

Ethos. We attach great importance to attracting the best possible research students and providing an environment in which they are likely to flourish.

Scholarships and recruitment. We receive on average over 25 applications for every place on our PhD programme. Some of the best applicants have PhD funding from their home university or government, but not all are in this position and so, to maximise the quality of our intake, we offer our own scholarships. Since 2008 we have developed a substantial departmental research scholarship scheme and a direct consequence is that our PhD student numbers have increased considerably, despite the withdrawal of EPSRC project studentships and our larger proportion of early career staff, who cannot sole-supervise. In 2013/14 we offer 10 full (fees plus stipend) departmental scholarships, 6 departmental-fees only Dixon scholarships and around 5 EPSRC Doctoral Training Grant full scholarships. In addition, our applicants compete, with our support, for College scholarships including Imperial PhD Scholarships (50 are awarded each year from 2012) and scholarships from funded centres including Grantham Institute and Energy Futures Lab. Approximately 34% of our intake are women, 25% are from the UK, 32% from other EU countries

and 43% are from overseas. Students submit a research statement which helps to match interests with potential supervisors. All prospective research students are interviewed by at least two experienced/trained academic staff and references are taken before offers are made.

Training and support. The PhD Committee oversees the format and quality of all aspects of the PhD programme. Students are based in one of our 5 Sections and have a main supervisor, the majority also have a second supervisor, and a mentor. All academic staff are trained in PhD supervision. Students in the same Section are located together. An induction day introduces the College and Department, our support services and research expectations. All students receive a postgraduate student handbook and regular events are organised for PhD student training and cohort building. Students are encouraged to attend relevant MSc modules (there are 115 offered by this Department alone), research seminars and other events. All PhD students are required to attend training delivered by the College Graduate School which includes a 3-day residential research skills development course and training in outreach and public engagement. Support is provided to allow all students to participate in at least one international conference.

Progress monitoring. We have comprehensive procedures to help students complete within 4 years, including our Director of PhD Programme and PhD Tutor monitoring progress with checkpoints at 3, 9 and 18 to 24 months and ensuring that adequate feedback and support are provided. Since 2011, 93.1% of our PhD students have completed within 4 years.

Degrees awarded. We graduated an average of 29 PhD students/year over the REF period, 47% up on RAE2008 and this will increase to 40 PhD students/year over the next few years. Our current graduates-per-academic data reflect our recent proportion of 1/3 (17 from 52) of our academic staff being early career academics appointed since January 2011 who have not been in the Department long enough to supervise PhD students through to completion.

Career progression. The Imperial Graduate School development programme supports our postgraduate students and places particular emphasis on helping them prepare for their future careers. Imperial is the only university to have won two Times Higher Education Awards, one for its innovative and integrated approach to supporting young academics and the other for initiating a course called *Finish Up, Move On*, aimed at helping PhD students complete their PhDs and progress their careers. Approximately half stay in academia while half take jobs in industry.

Our supportive and stimulating environment ensures that research students can thrive and contribute to the vibrant academic life in the Department, as well as becoming members of their subject's international research community.

d. Income, infrastructure and facilities

d.1 Infrastructure and facilities

The Department is housed in the **Skempton Building**, a dedicated 7 storey building of 7,700 m². Since 2008, more than £12.3m has been invested to improve and extend the capabilities of our laboratories, to create new teaching, seminar and computing rooms and to upgrade our research rooms and library. We have very large and exceptionally well equipped laboratories, supported by 15 full-time technicians:

Hydrodynamics Lab (1360m²) houses a (20mx12m) directional wave basin, a 65m long wave flume / towing tank, a shallow water coastal flume, a wind-wave-current flume, an instrumented pipe network, and a shallow water visual tank (7mx20m) complete with 3D motion rig. Research concerns offshore, coastal, environmental, and renewable energy applications. Having undergone a major (multi-million pound) refurbishment in 2004-5, a further investment of £2.4m has been made since 2008, with the College creating increased research student space, up-dated laser equipment and a new recirculating flume and industry funding the instrumented pipe network (NEC and ABB), new wave paddles for the towing tank (Shell UK) and the 3D motion rig (BP).

Structures Lab (1020m²) provides a large scale state-of-the-art testing facility incorporating a strong floor and overhead cranes. Refurbishment work completed in 2011 provided an investment of over £6m in the laboratory infrastructure including a new workshop and controlled concrete preparation areas as well as £2m for new servo-hydraulic test equipment with static, dynamic and impact loading capabilities. Multi-axial, cyclic/fatigue, creep, and elevated temperature tests can be conducted with loads up to 10MN with advanced control and non-contact data acquisition.

Environment template (REF5)

Concrete Durability Lab (128m²) moved into refurbished accommodation with upgraded equipment (total cost since 2010, £1.7m) which now includes facilities for environmental exposure, corrosion monitoring, microscopy (including a field emission scanning electron microscope with new x-ray system and a confocal microscope), chemical analysis (including a new X-ray fluorescence spectrometer), pore structure characterisation (including a new porosimeter) and a wide range of molecular transport measurements.

Geotechnics Lab (296m²) accommodates unique facilities for developing and applying advanced testing, including 13 heavily-instrumented automated stress-path triaxial cells (two for high-pressures), particle-scale and interface-shear apparatus, specialist cyclic, dynamic and unsaturated soil equipment and three Hollow Cylinder Apparatus' for 4-D stress-path probing. Investments since 2008 include new temperature controls (£300k), hollow cylinder upgrade (£32k), new large stress-path cells (£50k), micro-mechanics and particle characterisation equipment (£270k) and major new instrumented model tunnel and pile testing systems (£200k).

Environmental Chemistry, Microbiology and Waste Management Labs (592m²) provide state-of-the-art facilities for chemical and microbiological research, testing prototype treatment technologies and novel materials, supported by a wide range of analytical techniques including GC-MS, HPLC, ICP-OES, FTIR, AAS, UV-VIS, TOC, TGA, Analytical Pyrolysis and Bomb Calorimetry. Since 2008, approximately £800k has been spent on equipment (£624k Industry, £174k EPSRC/EU/TSB).

Intelligent Infrastructure and Transport Lab will provide capabilities for integrating real time sensing with simulation systems, and synthetic environments for scenario analysis. £485k has been spent to establish the lab's infrastructure. In 2014 existing experimental resources (~£1.6m) will be consolidated and an advanced modelling and analysis suite created.

Equipment sharing. Imperial runs an equipment sharing scheme. We have used a wide range of equipment from other departments including microCT in Materials, FTIR in Chemistry, air pollution monitors from Medicine and Geophysics logging equipment from Earth Sciences and Engineering.

Computing. The Department has access to extensive Computing facilities. In addition to general provision (120 PCs in 3 cluster rooms, one of which was created in 2012), we provide desktop PC's for researchers and fund generic research software (e.g. MATLAB, MAPLE, ABAQUS). Groups active in numerical modelling have dedicated computing clusters. We also contribute to and make heavy use of the College-wide HPC facility, which has around 14,000 cores (one of the UK's largest) and has seen an investment of £5.05m since 2008.

Civil Engineering Library. This library houses the second largest civil engineering collection in the UK after the ICE and shares a catalogue with the ICE. We invested £70k in refurbishing the library in 2013.

Research offices. Investment of £350k since 2008 has left all offices attractive and well furnished.

Imperial West. The College has recently acquired a new 22.75 acre Imperial West campus in Hammersmith. This offers the Department scope to continue to grow, either by creating new facilities at Imperial West or by developing vacated space in South Kensington.

d.2 Research funding

Imperial has a transparent funding model where departments receive all the income they earn from teaching and research and then contribute pro-rata towards central College costs. This model facilitates the estimation of future income and helps our long term resource planning.

The Department's research income has more than doubled since RAE2008 from an average of £3.33m/yr to £6.73m/yr, building on the step change from £3.49m to £5.47m in the final year of the RAE2008 period. A concerted effort has been made to become less dependent on UK government funding by increasing our EU, industry and charity supported programmes. Over the REF period EU Government funding increased from £0.42m to £1.15m/yr, while global industry and charity income increased from £2.05m to £3.26m/yr and £0.33m to £1.25m/yr respectively.

When considering research income per academic, it should be noted that 17 of our 52 academic staff are early career academics appointed since January 2011 and 9 of these were appointed in 2013 and these staff have not yet contributed substantially to our research income.

Environment template (REF5)

Our research funding priorities for the next five years are to:

- secure RCUK funding to support the exciting ideas of our newly appointed lecturers;
- win prestigious fellowships (e.g. ERC) to develop the research of some of our experienced academics;
- raise further funding to increase the number of fully funded PhD scholarships that we offer via various mechanisms including thematic programmes supported by industry clubs; and
- develop research projects associated with, and funded by, major infrastructure projects; we have done this with Thames Tideway and Crossrail (*Standing et al*), are about to start EDF Energy funded research for Hinkley Point (*Buenfeld*) and are negotiating in relation to HS2.

d.3 Consultancies and professional services

High level, intellectually challenging, consulting work provides a vital interface through which staff can interact with research users and gain insight into societal and industrial research needs. This professional engagement generates new topical and relevant research ideas, can lead to industrial research funding and provides a speedy and effective route through which our research can make a significant impact in engineering practice. Around 70% of the consultancy work carried out through the College Company (IC Consultants Ltd) meets HEFCE research criteria. This activity adds to the vitality of the Department, while the £150k per annum funding returned to the Department funds PhD scholarships. Examples that affected practice notably are included in our impact case history set, while others that helped set our research agenda include:

- Gerrards Cross tunnel collapse (HSE): *Nethercot, Potts, Zdravkovic and Ruiz-Teran's* novel modelling replicated the observed failure conditions and identified failure causes (2010-2013).
- Great Man-Made River, Libya: *Buenfeld* developed and trialled measures to enhance the durability of the concrete structures forming the world's largest civils project (2002-2011).
- Nuclear Plants in South Africa: *Stafford and Bommer* undertook SSHAC Level 3 Probabilistic Seismic Hazard Analysis (2008-09, 2011-2013) in a previously sparsely studied region.
- Nitrogenous disinfection by-products in drinking water (DWI): *N Graham and Templeton* surveyed concentrations of these compounds in 20 water supply systems across 6 water companies to help DWI decide whether to regulate these compounds (2011-12).
- Low carbon buildings (AREVA): *Keirstead* led analysis that is being carried forward in new research on the costs of 2050 low carbon scenarios for the global buildings sector (2012).
- Brent Delta (Shell E&P UK): *Swan* determined velocity amplification factors appropriate to the calculation of fluid loads on new subsea infrastructure to be installed as a vital part of the largest offshore decommissioning project ever undertaken (2011-12).

Numerous requests to undertake testing studies for industry are also received. These are only taken up if the work is interesting technically and can add positively to on-going research.

e. Collaboration and contribution to the discipline or research base**e.1 Collaborations**

Support for multidisciplinary research is central to Imperial's mission, and is strongly encouraged by the Department. Our size allows us to appoint staff from a broad range of backgrounds, in addition to civil engineering. Our staff have degrees in maths, physics, chemistry, natural sciences, bioscience, geology, materials, environmental science, aeronautical, mechanical and electrical engineering and economics, as well as civil engineering. This creates a fertile environment for collaboration within the Department and across the College and we have active collaborations with all 14 other academic Departments including our Business and Medical Schools.

Our research that addresses global societal challenges is often multidisciplinary; to facilitate this we establish or contribute to cross-cutting centres and institutes that operate across Imperial.

- **Energy Futures Lab.** *Spinneken* is Deputy Director. We have made 5 lectureship appointments in energy since 2010: *Spinneken* (marine renewables), *Taborda* (geothermal), *Christou* (offshore), *Tsiampousi* (nuclear) and *Keirstead* (urban energy systems) and these staff provide a link for many others to engage in energy-related research.
- **Grantham Institute for Climate Change.** *Buytaert* is funded by the Institute and leads the Water theme. *Polak, Keirstead* and *Buytaert* have been UK theme leaders of the EIT Climate

Environment template (REF5)

Knowledge and Innovation Community (Climate-KIC) and have involved many other departmental staff in this agenda.

- **Institute for the Environment.** We are playing an active role in establishing this new College Institute which will be launched in 2014.
- **Urban Systems Lab.** Polak is leading this new initiative which will address the challenges of an unprecedented scale of global urbanisation. It will bring together under a single banner the 200+ researchers across College working on urban issues to stimulate new research collaborations, enhance interaction with industry and government and contribute to public policy and thought leadership. It will work closely with the TSB's Future Cities Catapult, based in London and with academic partners in Asia and Latin America. We have recently appointed 2 new lecturers in urban engineering (*Angeloudis* and *Sivakumar*) to support this initiative.
- We are also active members of the College's *Centre for Nuclear Engineering, Digital Economy Lab, Institute for Security Science and Technology, Manufacturing Futures Lab* and *Centre for Blast Injury Studies*.

All academic staff have active national and international collaborations with other universities. These collaborations are too numerous to detail here, but cover 17 of the world's leading civil engineering departments (ranking based on QS 2013) and include:

- **Student exchange programmes:** currently with ENPC Paris Tech, ETH Zurich, Grenoble, Melbourne, Queensland, RWTH Aachen, TU Delft, UC Berkeley, UP Madrid, Hong Kong Polytechnic University and UPC Barcelona.
- **Visiting roles at other institutions:** e.g. in China, *Graham (N)*, *Jardine* and *Ochieng* are Visiting Professors at Hong Kong PolyU, Zhejiang and Harbin IT Universities respectively.
- **Multi-institution projects:** e.g. *Buytaert* leads a project (11 nations, £1.8m) on citizen science for water resources management in remote mountain regions (Peru, Ethiopia, Nepal, Kyrgyzstan).

Collaboration with Industry is very strong, with many industrial organisations involved closely in our research by participating in agenda setting, funding, the research activity and the application of our findings. Examples include:

- **Centres:** 3 centres established and based in our Department are fully funded by external sponsors:
 - *Laing O'Rourke Centre for Systems Engineering and Innovation;*
 - *Lloyds Register Foundation Transport Risk Management Centre;* and
 - *Railway and Transport Strategy Centre* (funded by 70 public transport operators).
- **Industrially funded posts:** Since 2008, seven of our academic posts have been funded by industry – two chairs fully-funded by Laing O'Rourke and Geotechnical Consulting Group (*Fisk* and *Potts*), two chairs co-funded by RAEng and industry (SITA - *Grimes*, BP – *Fisk* prior to 2010) and 3 lectureships fully funded by Lloyds Register Foundation (*Majumdar*), Grantham (*Buytaert*) and Willis (*Stafford*).
- **Visiting Professors:** For example, *Balmforth (MWH)*, *Cook (Buro Happold)*, *Davies (Laing O'Rourke)*, *Powderham (Mott MacDonald)* and *Wilson* (consultant) have had a substantial influence on our research agenda.
- **Industrial Doctorate Centres:** currently, we offer a 4 year EngD in Water Engineering funded through the EPSRC STREAM Industrial Doctorate Centre for the Water Sector. Each research student has an industrial sponsor and spends 75% of their time working with the company.
- **Research Consortia:** e.g. *Buenfeld* and *Wong* are active participants in NANOCEM, a cement and concrete science consortium, involving most of the world's major producers who fund coordination, technical events, proposal development and research projects.
- **Industry-led research projects:** e.g. we are the only UK university involved in Co-operative Vehicles and Infrastructure Systems (CVIS) a €41m EU project involving 61 partners to develop, integrate and evaluate co-operative vehicles and infrastructure systems.
- **Knowledge Exchange Partnerships:** e.g. researcher (*Coughlin*) funded by Environment Agency and Defra, under the direction of *Grimes*, to identify and facilitate collaborative research opportunities between academia and Defra/the Environment Agency.

e.2 Academic leadership and contributions to the discipline or research base

We are highly rated in all research-based tables - the 2013 QS international league tables placed Imperial 1st in Civil Engineering. Evidence of our academic leadership role in research collaborations and achievements is set out in earlier sections, particularly in b.2 and e.1. Our outputs include more than 900 journal papers, 950 refereed conference papers, 33 books and 90 book chapters over the REF period.

The Department encourages staff to take a leading role in **learned societies and professional associations** and provides cover and support for major commitments. *Nethercot* is President of the International Association for Bridge and Structural Engineering; *Balmforth* is the next President of The Institution of Civil Engineers; *Fisk* is Past-president (2012-3) of the Chartered Institution of Building Services Engineers; *Elghazouli* is Past-chair (2010-12) of the Society for Earthquake and Civil Engineering Dynamics. *Burland* is on the Royal Society Membership Committee and *Buenfeld* and *Jardine* are on the RAEng Membership Panel. We contributed to many learned society committees. For example, focussing on some of our female staff, *Grimes* sits on the ICE Waste and Resources management Board, while *O'Sullivan* was elected to the Council of Engineers Ireland, *Ruiz Teran* is on the Council of the Concrete Bridge Development Group and *Zdravkovic* is a member of the Executive Committee of the British Geotechnical Association.

5 current staff (*Buenfeld, Fisk, Jardine, Ochieng and Potts*) and 7 Emeritus staff (*Burland, Dowling, Neal, Nethercot, Ridley, Wheeler, Wyatt*) are **RAEng Fellows**, as are many of our Visiting Professors. *Burland* and *Dowling* are also **Royal Society Fellows**.

Staff have held over 160 invited appointments to prestigious **government, professional and technical committees** worldwide. Those advising government include: *Evans* - member of the Parliamentary Advisory Council on Transport Safety; *Bommer* - member of the Office of Nuclear Regulation, Expert Panel on Seismic Hazard and Climate Change; *Fisk* - board member of Ofgem; *Polak* - member of Greater London Authority's Smart London Board; and *D Graham* - adviser to the European Council of Transport Ministers.

Contributions to the development of **British and International standards** include Chair roles: *Gardner* UK Mirror Group for Eurocode 3; *Nethercot* - Committee B/525, British Standards in civil engineering and building structures as well as IStructE's Eurocodes Implementation Committee. Memberships include: *Elghazouli* - BS525/8 Seismic Design; *Jardine* - International API and ISO Panels for fixed and jack-up offshore structures and *Vollum* - BS525/1 on Concrete Design.

Our staff are **Editors in Chief** of 4 major journals: Computers and Geotechnics (*Potts*), ICE Structures and Buildings (*Gardner*), International Journal of Steel Structures (*Gardner*) and Urban Water Journal (*Maksimovic*) and are on the **Editorial Boards** of over 50 journals.

Keynotes and organisation of conferences. Our staff gave more than 200 keynote and plenary lectures and were involved in organising 92 conferences during the REF period. International conferences that we organised at Imperial include the IABSE International Conference (2011), Cement and Concrete Science (2011), International Symposium on Tubular Structures (2012) and the European Fluid Dynamics Postgraduate Conference (2012).

Research awards/prizes from the ICE include: Geotechnical Research Medal, 2013 (*Burland, Standing*); David Hislop Prize, 2013 (*Sobey*); Telford Gold Medal, 2010 (*Graham, Maksimovic, Stoianov*); Manby Prize, 2010 (*Fenton, Jardine*); Howard Medal, 2010 (*Popo Ola*); MCR Award, 2009 (*Buenfeld, Hong*), 2008 (*Khoury*); Palmer Prize, 2008 (*Gardner*); Geotechnical Research Medal, 2008 (*Jardine*); Trevithick Prize, 2008 (*Wadee*); Bill Curtin Medal, 2008 (*Potts*).

Research awards/prizes from other institutions include: ISSMGE Outstanding Paper Award, 2013 (*Burland*); ISWA Publication Award, 2013 (*Cheeseman, Smith, Wilson*); ISSMGE Bishop Honour Lecture Award, 2013 (*Jardine*); BGA Medal, 2012 (*Potts, Zdravkovic*); 2010 (*Zdravkovic*); 2008 (*Kontoe, Potts, Zdravkovic*); RIN Michael Richey Medal, 2011 (*Ochieng, Schuster*); CIWM Wastes Regulation Award, 2011 (*Grimes, Wilson*); DSc Honoris Causa, University of Hertfordshire, 2011 (*Burland*); NCF Wim Nieupoort Award for Super-Computing, 2010 (*Van Reeuwijk*); IStructE Gold Medal, 2009 (*Nethercot*); ACES Academic Enterprise Europe award, 2009 (*Cheeseman*); FIB Diploma, 2009 (*Ruiz-Teran*); ECCS Charles Massonet Prize, 2009 (*Nethercot*); IACMAG Outstanding Contributions Award, 2008 (*Potts*); IMA Catherine Richards Prize, 2008 (*Wadee*).