GEOTECHNICAL, GEOLOGICAL AND EARTHQUAKE ENGINEERING

GEOTECHNICS AND EARTHQUAKE GEOTECHNICS TOWARDS GLOBAL SUSTAINABILITY

SUSUMU IAI
EDITOR

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Geotechnics and Earthquake Geotechnics Towards Global Sustainability

Edited by

SUSUMU IAI
Kyoto University, Kyoto, Japan

Prologue by Michael J. Pender

Springer

Editor
Susumu Iai
Disaster Prevention Research Institute
Kyoto University
Gokasho, Uji
611-0011 Kyoto
Japan
iai@geotech.dpri.kyoto-u.ac.jp

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Preface

Global sustainability is the greatest long term challenge of our time. The breadth of disciplines that need to work together and the long duration over which action must be coordinated is unprecedented in the history of engineering. In geotechnical engineering and earthquake geotechnics in particular, we are unused to the challenge of working with other disciplines to address such problems, which have been far removed from our daily practice to date.

This book is the result of a new initiative: it is intended to be an initial, bold step towards approaching this challenging subject from the discipline of geotechnical engineering and earthquake geotechnics through the contributions of thirteen world leading experts. A special seminar was held in Kyoto, Japan, hosted by the Kyoto Sustainability Initiative, from January 12–14, 2010, which brought a number of experts together to discuss the opportunities for geotechnical engineering and earthquake geotechnics as we face up to this global challenge. The seminar generated intensive and stimulating discussions on a wide range of topics from the purely technical to government policy. Following the seminar, each of the experts was invited to set down their thoughts, from which this book has been prepared.

Soil in one form or another covers most of the surface of the planet, and yet soil mechanics as such does not seem to be a big factor in global sustainability. The subjects covered by the international experts in this book include an overview of global sustainability, geotechnical challenges in counteracting natural hazards, the role of geotechnical engineering in creating a low carbon society, world heritage, lifelines in megacities, coastal protection, exploring non-gravity geotechnics, designing for sustainability and more. We hope that these contributions from the Kyoto Seminar 2010 will stimulate debate over the role of geotechnics in achieving a more sustainable future for the world.

The compilation and editing of this book coincided with the initial phase of activities of Technical Committee 303 (TC303) “Coastal and River Disaster Mitigation and Rehabilitation” (short name “Floods”), a new Technical Committee (TC) of the ISSMGE created for the period 2009–2013 under the wider theme of “Impact on Society”. TC303 continues the work of the former TC39 “Geotechnical Engineering for Coastal Disaster Mitigation and Rehabilitation”, which was focused on tsunami risk following the 2004 Sumatra earthquake in Indonesia. The editing of this book reflects the activities of TC303.

In compiling the manuscripts, the assistance by Ms. Waka Yuyama, Kyoto University, is gratefully acknowledged.

Uji, Kyoto Susumu Iai

Prologue: Designing for Sustainability

From the Big Picture to the Geotechnical Contribution

Michael J. Pender

1 Introduction

Many of the contributions to this volume make clear that sustainability is a broad concept embracing multiple distinct facets. In this prologue some of the wider aspects are discussed briefly, particularly in relation to earthquake geotechnical engineering. This is preceded with comments on the motivation for the drive towards sustainability both from an aesthetic viewpoint and a practical one.

2 Natural Beauty of Our World – One Motivation for Sustainable Development

A few days before travelling to Kyoto, one sunny summer afternoon at my home in Auckland, whilst I was preparing my presentation for the seminar, I looked out the window and saw a kingfisher (a small brightly coloured bird) perched on a stake that had been driven into the ground to support the tomatoes growing in our vegetable garden (Fig. 1). A few haiku-like lines popped into my mind. With a bit of polishing these became:

Kingfisher perched on garden stake,
plumage iridescent in sunlight.
Oh, the joys of summer!

This seriously infringes the haiku 17 syllable rule, but I hope it expresses the delight we all experience when, unawares, we are suddenly struck by some facet of the marvellous beauty of the world we inhabit. The mention of summer probably reflected my subconscious realisation that going to Kyoto, an invitation which I accepted with much delight, meant forgoing part of the peak summer holiday season in

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M.J. Pender (✉)
Department of Civil and Environmental Engineering and Geotechnical Engineering,
University of Auckland, Auckland 1142, New Zealand
e-mail: m.pender@auckland.ac.nz

Fig. 1 One sunny summer afternoon in the vegetable garden at my home in Auckland

New Zealand. Often in January my wife and I enjoy camping at a seaside location. This involves putting the bright lights of Auckland far behind us. On a clear moonless night I like to leave our tent at 2 or 3 am to gaze at the myriad stars overhead in the Milky Way. This awe inspiring view is not available to city dwellers, thus the few occasions a year that I can be so amazed are very memorable. Another enjoyable aspect of camping near the seaside is walking along the beach on the firm wet sand exposed at low tide, noting the dilatant response of the sand with every footfall, enjoying the crash of the breaking waves in the surf on one side, and wondering at the green forest-clad rolling hills on the other. After some days of these delights one returns to the city refreshed.

Many striking photographic images have come to define aspects of the twentieth century, some, of course, quite horrible. One that has rightly achieved iconic status is the view of the earth first obtained from within the lunar orbit during the Apollo programme of the 1960s. Ever since the time of Galileo people have gazed at the planets through telescopes and wondered about conditions there and the possibility of life existing in these distant worlds. But compared with the view of the earth from near space these planets look quite uninteresting. The great surprise was the realisation that our planet is very beautiful and yet seems to be so delicate (Fig. 2). At the time of the first moon landing Norman Cousins, a columnist in the New York Saturday Review, made an important observation:

> What was most significant about the lunar voyage
> was not that men set foot on the moon,
> but that they set eye on the earth.

The beauty of this image must surely have been a formative influence in the ever strengthening realisation in the final 3 or 4 decades of the twentieth century that our

Fig. 2 The earth as seen from within the lunar orbit

planet is finite and could be damaged irreparably by rapacious human exploitation. This is not to say that prior to the 1960s people had not realised that environmental matters were a vital concern. In the late nineteenth century John Muir championed the natural beauty of the Yosemite region of California; many students of English poetry have been captivated by Wordsworth's eighteenth century feeling for the beauty of nature expressed in his poem "Daffodils"; and about a century earlier than Wordsworth, Basho, during his wanderings around Japan, was able to capture in so few syllables the endless fascination of nature. Perhaps one could use the insights of these prescient individuals as a pointer to an innate human appreciation of the beauty of our world. Even so, the realisation that the resilience of our planet could not be taken for granted slowly dawned for large numbers of people only during the second half of the twentieth century. The image of earth from space has become a visual expression of this understanding.

Thus it is very clear that the major driver in our present concern about sustainability is the widely perceived worry about the ability of our planet to survive the demands placed on it by humanity. I think the first reason for our concern about the future of the earth is an aesthetic one: With our knowledge of the beauty of the earth, how could we be so negligent as not to commit ourselves to preservation? The second is a moral reason: Who are we to destroy what we have inherited or to pass on to future generations a seriously depleted planet? Finally, there is a practical reason: If we do not protect the earth there is a very real possibility that life on our planet will be snuffed out.

3 Sustainability

As stated above sustainability is an all-embracing concept, and consequently it is often dismissed as being too vague. Although a universally accepted definition might be difficult to reach, the following are important components of sustainability. First, the earth's resources need to be used wisely and with particular attention to avoiding waste. Second, energy supply and use has become a critical question along with the accompanying threat of global warming. Third, sustainability must also encompass the idea of equitable sharing of the earth's resources. Clearly, there are issues of justice involved if some parts of the human population consume far more than their fair share of what our planet can produce whilst others are deprived.

4 Global Warming

The question of energy production and global warming is currently very important. The big issue is whether or not there is a link between energy produced by burning fossil fuels and global warming. The sceptics say that the scientific evidence produced so far is not convincing. But it is undeniable that the amount of carbon dioxide being spewed into the atmosphere has been increasing at an accelerating rate since the beginnings of the Industrial Revolution. An aspect of engineering thinking is the making of decisions with imperfect or incomplete information, thus it requires judgement. Consequently an engineering approach to global warming is to admit that, although we may not have certain evidence at present, the risk of deferring action until definite evidence comes to hand is too great. This means that it is simply a matter of prudence to take action now to control the outputs that are thought to be contributing to global warming.

5 Transport Fuels

Worldwide there is much interest in renewable energy sources. Wind, wave and solar generation of electricity are undergoing accelerated development. These and other approaches are thought to have considerable potential in leading to better ways of producing electricity for homes, offices and factories. Much interesting information about the energy question is given in MacKay (2009).

More problematic are transport fuels. Some think the electric car, recharged from mains electricity overnight, has potential to fulfil needs for short distance travel in cities and towns in a way that is much more satisfactory than the present use of fossil fuels. Challenges with longer distance travel remain. Even more challenging is the question of air travel. Air travel has about the same energy consumption per passenger kilometre as car travel (McKay, 2009), but the great distances people travel by air means that vast quantities of combustion products are released at locations where the atmosphere is easily damaged. At present it is not clear what alternative fuels are possible for this transport medium.

More than half the presenters at the seminar travelled considerable distances by air to reach Kyoto. We could be asked, given the electronic media available today, if this was justified. Coming from a remote part of the globe I wish to emphasise the importance of air travel. When young people of my parents' generation wanted to travel to Europe or North America from New Zealand they had to spend weeks onboard ship. Now I can complete the journey to Europe in not much more than a day. Travel to North America or Asia is accomplished in half a day or less. In my professional life I have enjoyed the privilege of participating in international meetings and visiting colleagues in most parts of the world. I am sure that this mobility contributes to the effectiveness of our profession, to the growth of knowledge, and to improvements in engineering practice. Even more it has developed an international community able to pool knowledge and insight; with the advantage that rapid implementation becomes possible. Perhaps even more important though, is the way air travel has made people from all corners of the globe aware that our shared humanity is much more significant than our differences. I think this has produced a remarkable sense of belonging to the human family, in this way one can even defend air travel as a means of tourist transport to say nothing of the contribution tourism makes to local economies around the globe.

6 Geotechnical Engineering – Big Contributions to Sustainability

A perusal of the Table of Contents of this volume illustrates that many facets of the application of geotechnical understanding to sustainability issues are covered by the contributors. Clearly advancing understanding of earthquakes and other natural disasters is a fertile field for contributions by the geotechnical profession to sustainable development.

Yet there is more that could be done. Last year the University of Auckland had a visit from Martin Fisher, a Stanford PhD graduate in mechanical engineering, who had spent time in Kenya on a Fulbright scholarship. While in Kenya he realised that water for irrigation of crops was the great need. He developed a simple human-powered water pump that can draw well water from depth. This can be manufactured at modest cost and has transformed the lives of many families giving them economic independence (Fig. 3). The website of this group – www.kickstart.org – tells the story. From water pumps they have moved onto other products. One of these is a human-powered press for the formation of building blocks from soil. With one bag of cement about 100 blocks can be produced in a day. This means that with simple equipment construction of dwellings is possible with local materials. However, with further geotechnical work it might even be possible to develop processes for making building blocks that require no cement, which will clearly be a contribution to sustainability given that the manufacture of cement requires a high energy input. This development would require understanding of the properties of soil, containing at least some clay, at very low water content. This is a potential joint research topic between a sophisticated geotechnical laboratory somewhere in the developed world with field workers in the developing world. About one third of the world population

Fig. 3 Human-powered irrigation pump from *Kick Start*

live in houses constructed of mud bricks, or adobe, so the comments just made relate to what is already a well established process in many parts of the world. However, we know that dwellings constructed from unreinforced adobe and bricks perform extremely poorly in earthquakes. Examples are the Bam earthquake in Iran in 2003 and the earthquake in Peru in 2007 in which 80% of the housing in the town of Pisco was destroyed. We also know that the application of relatively simple engineering is able to greatly improve the performance of these structures. Building dwellings that can survive earthquakes must be high on the list of priorities that could contribute to a sustainable world. In many cases it appears that the barrier to the implementation of improved building practices is sociological rather than technical. Poverty levels are often such that people cannot afford the small additional cost of incorporating some reinforcing into their buildings or to construct roofing of lightweight materials. Here we have a challenge presented to the world community that has great bearing on sustainability but which is not a technical problem. We as geotechnical engineers can do our part, though, by endeavouring to influence decision makers in Governmental and non-Governmental organisations charged with improving the lot of those in relatively undeveloped parts of the world. A particular role we and our colleagues can fulfil is to quantify the improvements in sustainability that could be achieved from modest expenditure.

7 Recycling and Use of Natural Materials

In discussing the Kyoto sustainability seminar with colleagues at the University of Auckland, I learnt of several initiatives to recycle materials or to use natural materials in new ways. Apparently water based paint has a composition not much different from the additives used in concrete making. One paint company in New

Zealand offers a disposal service for left-over paint and one of my colleagues is investigating the effectiveness of this as a concrete additive and the properties of the resulting paint-crete. Another similar project is based on the use of crushed glass as a substitute for sand in concrete, so producing glass-crete. Auckland is an area with an impending shortage of concrete aggregate so work is being done on the recovery of aggregate from demolition concrete. Other colleagues are looking at the use of natural fibres as concrete reinforcing and another is investigating the effect of reinforced adobe in shaking table tests. Finally, another group is investigating the performance of natural fibre as reinforcing for rammed earth construction, a technique that may provide an inexpensive means of improving the earthquake resistance of adobe construction and so offer a solution to the problem discussed above.

These applications are not geotechnical as such but they point to ways of improving the sustainability that will be utilised alongside geotechnical work. So I conclude this prologue by emphasising that although geotechnical insight can make an important contribution to world-wide sustainable development, as demonstrated by the contributions to this volume, the way forward requires the marshalling of insights from many different disciplines, engineering and otherwise, and these groups, in turn, working together with the wider community.

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Contents

Contributors

Atilla Ansal Kandilli Observatory and Earthquake Research Institute, Boğaziçi University, Istanbul 34684, Turkey, ansal@boun.edu.tr

M. Asrurifak Faculty of Civil and Environmental Engineering, Institut Teknologi Bandung, Bandung 40132, Indonesia, m_asrurifak@yahoo.com

J.P. Bardet Department of Civil and Environmental Engineering, University of Southern California, Los Angeles, CA 90089-2531, USA; Center on Megacities, University of Southern California, Los Angeles, CA 90089-2531, USA, bardet@usc.edu

C.H. Chen National Taiwan University, Taipei, Taiwan, chchen2@ntu.edu.tw

Jian Chu School of Civil and Environmental Engineering, Nanyang Technological University, Singapore, Singapore 639798, cjchu@ntu.edu.sg

Craig A. Davis Geotechnical Engineering, Los Angeles Department of Water and Power, Los Angeles, CA 90012, USA, craig.davis@ladwp.com

W.D. Liam Finn Department of CE, University of British Columbia, Vancouver, BC, Canada V6T 1Z4, finn@civil.ubc.ca

Anita Firmanti Research Institute for Human Settlements, Indonesia Ministry of Public Works, Indonesia, anitafirmanti@yahoo.com

H. Hendriyawan Faculty of Civil and Environmental Engineering, Institut Teknologi Bandung, Bandung 40132, Indonesia, hendriyawan@ocean.itb.ac.id

Susumu Iai Disaster Prevention Research Institute, Kyoto University, Uji, Kyoto 611-0011, Japan; Kyoto Sustainability Initiative (KSI), Kyoto University, Uji, Kyoto 611-0011, Japan, iai@geotech.dpri.kyoto-u.ac.jp

Atsushi Iizuka Research Center of Urban Safety and Security, Kobe University, Nada-ku, Kobe 657-8501, Japan, iizuka@kobe-u.ac.jp

Masyhur Irsyam Faculty of Civil and Environmental Engineering, Institut Teknologi Bandung, Bandung 40132, Indonesia, masyhur.irsyam@yahoo.co.id

Kenji Ishihara Chuo University, Tokyo, Japan, kenji-ishihara@e-mail.jp

Yoshinori Iwasaki Cyber University, Fukuoka, Japan; Geo Research Institute, Osaka 550-0012, Japan, yoshi-iw@geor.or.jp

Aslı Kurtuluş Kandilli Observatory and Earthquake Research Institute, Boğaziçi University, Istanbul 34684, Turkey, asli.kurtulus@boun.edu.tr

Hamzah Latif Center for Marine and Coastal Development, Institut Teknologi Bandung, Bandung 40132, Indonesia, hamzah@ppk.itb.ac.id

Wei F. Lee Facilities and Assets Management Center for Infrastructures, National Taiwan University of Science and Technology, Taipei, Taiwan, weilee@mail.ntust.edu.tw

Michele Maugeri Department of Civil and Environmental Engineering, University of Catania, 95125 Catania, Italy, mmaugeri@dica.unict.it

Ernesto Motta Department of Civil and Environmental Engineering, University of Catania, 95125 Catania, Italy

Shintaro Ohno Advanced Analysis Group, Engineering Development Department, Civil Engineering Design Division, Kajima Corporation, Minatoku, Tokyo 107-8502, Japan, onosi@kajima.com

Hideki Ohta Research and Development Initiative, Chuo University, Bunkyo, Tokyo 112-8551, Japan, ohta@tamacc.chuo-u.ac.jp

Michael J. Pender Department of Civil and Environmental Engineering and Geotechnical Engineering, University of Auckland, Auckland 1142, New Zealand, m.pender@auckland.ac.nz

Nazili Razali Research Group on Eco-Hydraulic, Engineering Center for Industry, Institut Teknologi Bandung, Bandung 40132, Indonesia, nazili70@yahoo.com

Kenichi Soga Department of Engineering, University of Cambridge, CB2 1PZ Cambridge, UK, ks207@cam.ac.uk

R. Scott Steedman Steedman & Associates Ltd., W8 7ST London, UK, contact@scottsteedman.com

Gökçe Tönük Kandilli Observatory and Earthquake Research Institute, Boğaziçi University, Istanbul 34684, Turkey, gokce.tonuk@boun.edu.tr

Ikuo Towhata Department of Civil Engineering, University of Tokyo, Tokyo 113-8656, Japan, towhata@geot.t.u-tokyo.ac.jp

Thi Lan Anh Trinh Electricity of Vietnam, Dong Da District, Hanoi, Vietnam

Suguru Yamada Department of Civil Engineering, University of Tokyo, Tokyo 113-8656, Japan, suguru@geot.t.u-tokyo.ac.jp

Shuwang Yan Geotechnical Research Institute, Tianjin University, Tianjin, China, yanshuwang@tju.edu.cn

Chapter 1
Introduction

Towards Global Sustainability

Susumu Iai

Abstract As an introduction of Geotechnics and Earthquake Geotechnics towards Global Sustainability, this chapter reviews the fundamentals of global sustainability, including the status of climate change and the concepts of growth limits, strong and weak sustainabilities, and an ecological footprint. Based on this review, a conceptual framework of global sustainability is proposed as follows. Because humanity's burden has already exceeded Earth's biological capacity, an increasing number of regional systems may face critical conditions. Thus, studying the vulnerability and robustness of social networks and ecosystems is crucial in establishing a strategy to achieve sustainable development. The risk assessment approach combining the uncertainties in fragility and hazards is readily applicable to form a reasonable strategy in the adaptation and the risk management to the global climate and environmental change. In conventional design, construction of a good geotechnical work was the sole objective of design. In the merging trends in design for sustainability, providing appropriate function and service rather than the construction of a solid structure becomes the final objective of design. A new challenge is combined hazards, such as the combination of earthquake motions and tsunamis observed during 2004 Sumatra, Indonesia earthquake. Thus, radically new approaches and technologies must be developed in the near future.

1.1 Introduction

After the Earth was created 4.6 billion years ago, chemical reactions produced organic molecules. These molecules led to a crude form of a life. Four million years ago, human beings evolved, and their population grew to 5 million due to

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S. Iai (✉)
Disaster Prevention Research Institute, Kyoto University, Uji, Kyoto 611-0011, Japan;
Kyoto Sustainability Initiative (KSI), Kyoto University, Uji, Kyoto 611-0011, Japan
e-mail: iai@geotech.dpri.kyoto-u.ac.jp

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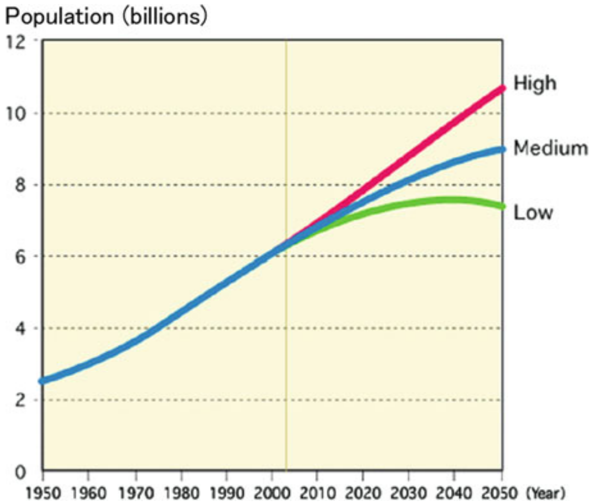


Fig. 1.1 World population projections, 1950–2050 (United_Nations, 2003)

the innovation of stone implements. The development of agriculture expanded this population to 500 million. During the ensuing 10,000 years, which was a period of little technological innovation, the population remained stable. Then the industrial revolution about 200 years ago triggered a population explosion, and the population reached 6 billion. In 50 years the population will reach 10 billion due to the technological revolution of the twentieth century (Fig. 1.1). This growth has consequently created an excessive burden on Earth's limited resources, which poses threats to human sustainability. The future of the Earth and humans depends on mankind's approach to solve these problems.

The objective of this chapter is to review the fundamentals of sustainability science as well as to provide a basic conceptual framework for the various approaches of geotechnics and earthquake geotechnics towards global sustainability. Although limited and minimal, this review includes sufficient materials to suggest specific approaches required for sustainability science.

1.2 Sustainable Development

The term sustainable development was defined by the Brudtland Commission of the United Nations (World Commission on Environment and Development, 1987) as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." This is the most quoted definition in the literature. The underlying notion behind this definition is the awareness that our planet has limited resources, and consequently unlimited development is impossible. A few decades ago, the Club of Rome commissioned an MIT research team to run a series of computer simulations on human growth for our planet. This culminated in the publication of "The Limits to Growth", which raised key questions about the sustainability of modern society. The primary findings are as follows (Meadows et al., 1972):

(1) If the present growth trends in the world population, industrialization, pollution, food production, and resource depletion continue unchanged, the limits of growth on this planet will be reached within the next 100 years. The most probable result will be a rather sudden and uncontrollable decline in both population and industrial capacity.
(2) These growth trends can be altered. Ecological and economic conditions, which are stable and sustainable, are possible. The state of global equilibrium can be designed so that the basic material needs of each person on Earth are satisfied, and each person has an equal opportunity to realize his or her individual human potential.
(3) If humanity decides to strive for this second outcome, the sooner this becomes a priority, the greater the chance of success.

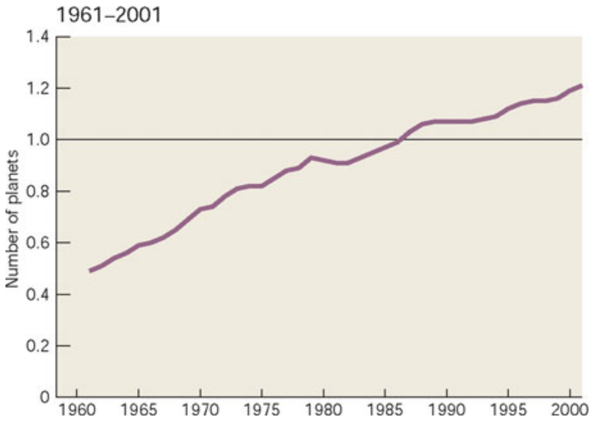
The most significant implication among these findings is even before reaching the physical limits of Earth's resources, society will suddenly and uncontrollably change. Thus, a core aspect of sustainability is to protect natural capital, including the ability of Earth to renew or regenerate itself. Strong (narrow) sustainability will maintain natural capital independent of human-made forms of capital. In contrast to focusing on maintaining natural capital, weak (broad) sustainability aims at preserving the value of all combined assets, including substitutes for lost ecological services produced by technology (Pearce et al., 1989).

Whether society pursues weak or strong sustainability, both paths need metrics to monitor various forms of capital. Thus, the concept of an Ecological Footprint has received much attention in both academic and political societies. An ecological footprint is a measure of the global ecosystem's capacity to reproduce natural (biomass) resources and to provide waste absorbing functions (Wackernagel et al., 2005). The ecological footprint is calculated based on the following seven areas using equivalence factors, whose 2001 values are denoted in parentheses (global hectares/ha):

(1) Cropland (overall = 2.1; primary = 2.2; marginal = 1.8)
(2) Pasture (= 0.5)
(3) Forest (= 1.4)
(4) Fisheries (= 0.4)
(5) Built-up area (= 2.2) (A built-up area is assumed to be located mostly on prime agricultural land; hence, a built-up area has the same equivalence factor as primary cropland.)
(6) Hydropower area (= 1.0)
(7) Fossil fuels (forest) (= 1.4)

Figure 1.2 shows the ecological footprint calculated for our planet from 1961 to 2001 (WWF, 2004). In 2001, the human burden on the global ecosystem was 2.5 times of that in 1961, and exceeded the Earth's biological capacity by 20%.

Fig. 1.2 Ecological footprint, 1961–2001 (WWF, 2004)



Although this dramatic increase does not imply an imminent collapse of our planet's sustainability, it does send an alarming signal related to our ability to achieve sustainable development.

Figure 1.3 shows the global temperature change predicted by IPCC. Even if the CO_2 emission is reduced to certain target levels in 50 years using appropriate mechanisms, such as the Kyoto Protocol, the CO_2 concentrations and related temperature

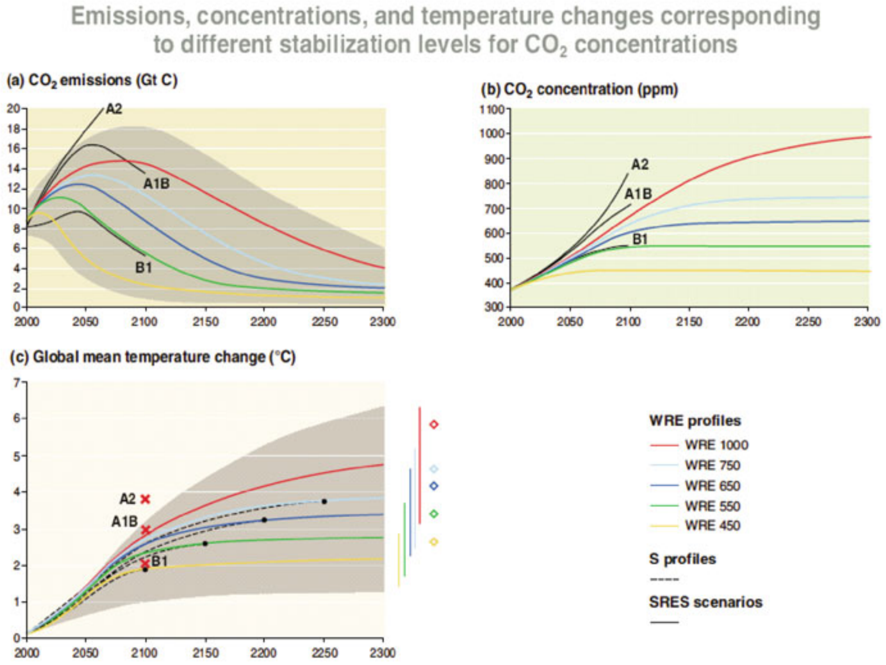


Fig. 1.3 CO_2 emissions and global temperature change (IPCC, 2001)

increases will continue for more than 100 years. More alarming is the sea level rise due to ice melting, which will continue over several millennia (IPCC, 2001).

1.3 From Global Sustainability to Regional Development

The current status of global sustainability reviewed in the previous section is the global average. The underlying mechanisms of these trends are functions of regional activities. For example, the ecological footprint is not uniformly distributed and varies drastically by region (Fig. 1.4). However, this type of map does not indicate the dynamics. Enormous amounts of natural resources are being transferred around our planet through imports and exports. As an example, Fig. 1.5 shows the exports from China in 2001. With rapid economic development in Asia, these flows of biocapacity will drastically change in the near future.

An awareness of these dynamics on the global scale is necessary to study regional sustainable development because regional systems are not closed. The impacts of inputs and outputs from regional systems may be significant for regional sustainability. Thus, trends and changes in the dynamics on the global scale may be closely related to regional sustainability. Ultimately, a study on the interaction between global and regional systems may be required. However, if carefully applied, geoinformatics can be a powerful tool for uncovering the relationships between these systems.

With the aid of satellite and other remote sensing techniques, data is available from various sources on a global scale. For example, Fig. 1.6 depicts natural resources in an animation format from NASA. Moreover, human statistics are available from the United Nations. A general global view of the Earth is available through free software such as Google Earth. With the aid of the Internet, considerable amounts of information on sustainability on the global scale are available.

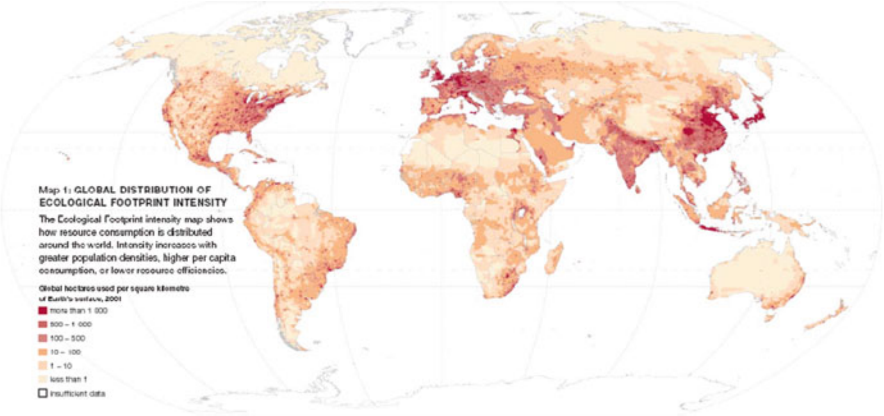


Fig. 1.4 Distribution of ecological footprint (WWF, 2005)

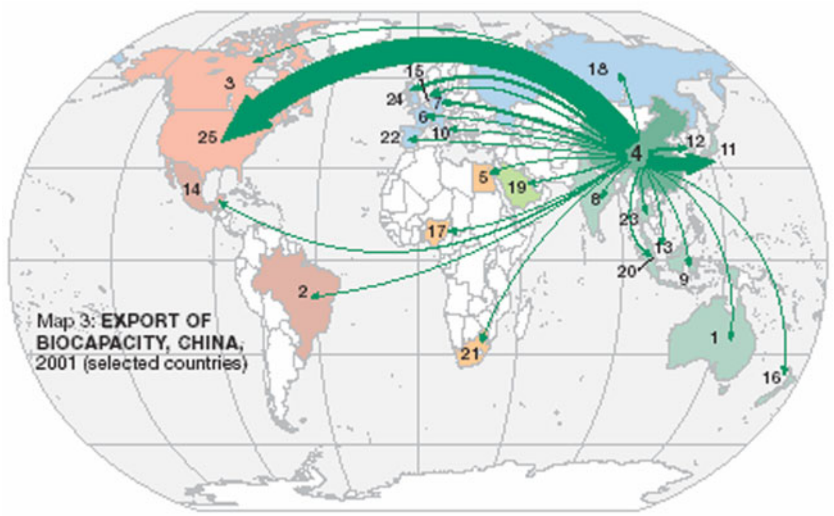


Fig. 1.5 Export of biocapacity, China (WWF, 2005)

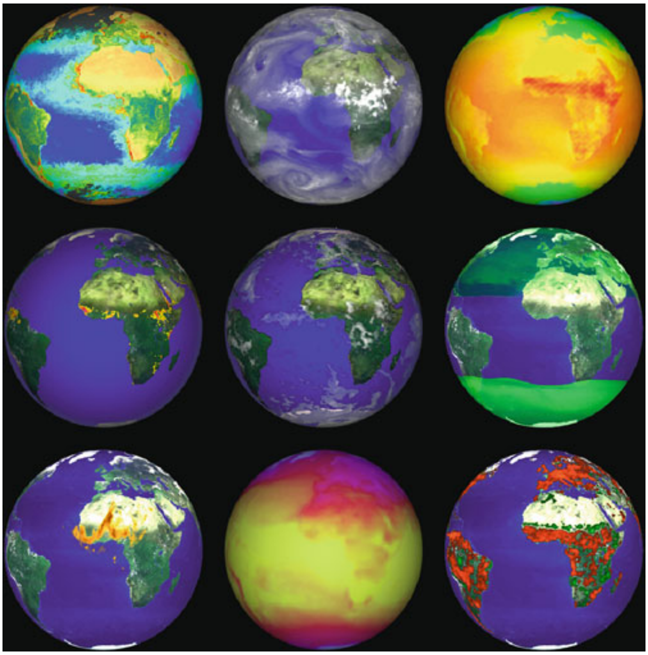


Fig. 1.6 (*left* to *right*, *top* to *bottom*) Biosphere, water vapor, temperature, fires, clouds, methane, aerosols, radiant energy, vegetation index anomalies (NASA/Goddard Space Flight Center, The SeaWiFS Project and ORBIMAGE, Scientific Visualization Studio)

These useful data sources have recently become available and are intended to be shared. At least in the initial phase, readily available data on the global scale can be useful to determine the general direction of a sustainability study.

1.4 Identifying Dynamics

Due to recent industrialization and economic growth, Asia will soon face huge increases in energy demands, especially for petroleum and natural gas. Infrastructure such as lifeline facilities will be rapidly constructed to accommodate these demands, and these rapid changes in social and urban systems will pose a threat to natural environments surrounding urban areas as well as the global environment. As a whole, social and urban systems will face a critical phase of vulnerability against external impacts such as natural disasters.

Indices such as temperature changes used to discuss global sustainability (Fig. 1.3) include both spatially and temporally averaged data. In addition to excluding annual, monthly, or daily variations, this data does not show anomalies or extreme highs or lows. Furthermore, extreme climatic events such as storms, typhoons, and high tides are missing. Thus, to achieve sustainability in a system currently progressing through a critical stage, a systematic response and vulnerability assessment to extreme events should be studied because such extremes often trigger threshold responses (i.e. natural disasters).

Identifying event sequences often leads to a reasonable understanding of the dynamics of social and natural systems. For example, a negative spiraling sequence of events can be recognized in natural disasters and poverty in society due to rapid industrialization and urbanization. Population growth in rural areas will push people to areas, which have yet to be cultivated and are vulnerable to natural disasters. Disasters and the ensuing poverty will force people to even more isolated and vulnerable areas. This rapid industrial growth requires cheap labor; thus, pushing younger generations towards urban areas. Then the population declines in rural areas as only older generations remain.

A positive spiral of events is also possible. For example, poverty in rural areas has been a major social problem in Brazil. Since new technology to efficiently produce ethanol from sugar cane has been developed and implemented, people in these areas are finding new jobs related to ethanol production. The produced ethanol is then put into use as part of the biomass energy, offsetting the human burden on the environment in these areas.

The above discussions can be summarized as follows. Differentiating positive and negative sequences may lead to a strategy to achieve a sustainable society. Identifying the dynamics of the concentration and dispersion of social systems and natural resources is essential for establishing harmonic societies. Moreover, elucidating the relationships between social systems and technological strategies is important. As humanity's burden has already exceeded Earth's biological capacity, an increasing number of regional systems may face critical conditions. Studying the vulnerability and robustness of social networks and ecosystems will aid in realizing a sustainable development strategy.

1.5 Dealing with Uncertainty

When evaluating uncertainty in the geotechnical structures for seismic hazard evaluation, the uncertainties in the fragility of a system and the hazard level the system is exposed are formally treated as follows. In this assessment, “failure” is defined by the state that does not satisfy the prescribed limit states typically defined by an acceptable displacement, deformation, or stress. If a peak ground motion input to the bottom boundary of soil structure systems is used as a primary index of earthquake ground motions, probability of failure $F_F(a)$ at peak ground motion a is computed considering uncertainty in geotechnical and structural conditions. A curve described by a function $F_F(a)$ is called a fragility curve (Fig. 1.7a). Probability of occurrence of earthquake ground motions is typically defined by a slope (or differentiation) of a function $F_H(a)$ that gives annual probability of exceedance of a peak ground acceleration a. A curve described by a function $F_H(a)$ is called a seismic hazard curve (Fig. 1.7b).

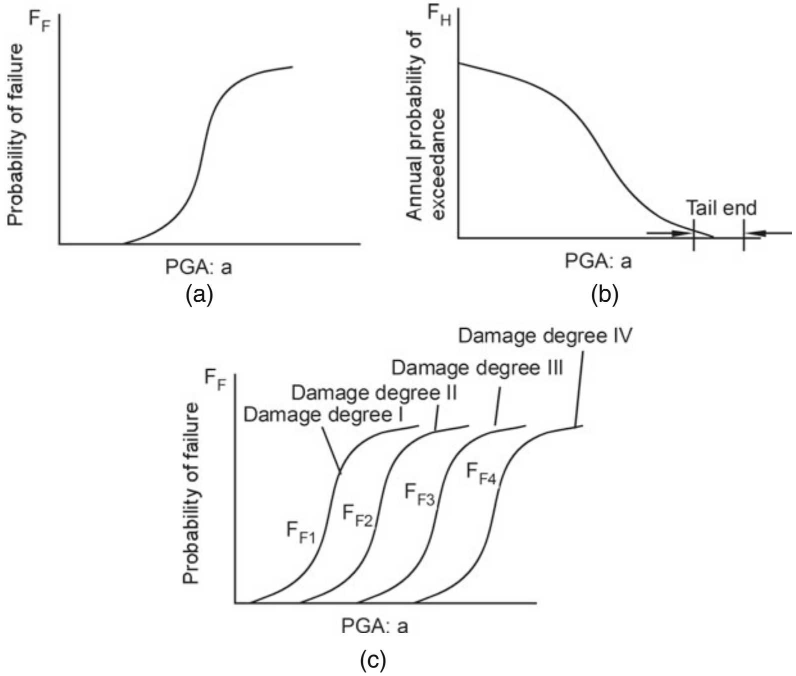


Fig. 1.7 Schematic figures of a fragility curve (**a**), a seismic hazard curve (**b**), and a group of fragility curves for multiple limit states (**c**)