Advanced Series on Ocean Engineering — Volume 39

LIQUEFACTION AROUND MARINE STRUCTURES

B. Mutlu Sumer

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Preface

In geotechnical-engineering terminology, liquefaction refers to the state of the soil in which the effective stresses between individual soil grains vanish and the water–sediment mixture as a whole, therefore, acts like a fluid. Under this condition, the soil fails, therefore precipitating failure of the supported structure such as pipelines, sea outfalls, breakwaters, seawalls, pile structures, gravity structures, rock berms, etc.

Although a substantial amount of knowledge had accumulated on flow and scour processes around marine structures, comparatively little was known about the impact of wave-induced liquefaction on these structures until recently. Indeed, the topic had received little coverage in research, which had substantially advanced the design of coastal structures but not the design of their foundations with regard to soil liquefaction.

The European Union (EU) supported a three-year (2001–2004) research program called LIquefaction around MArine Structures (LIMAS), which was preceded by another EU research program (1997–2000) called SCour ARound COastal STructures (SCARCOST) in which liquefaction around coastal structures was one of the two focus areas. The main results of LIMAS were published in two special issue volumes in the *Journal of Waterway, Port, Coastal and Ocean Engineering* by the American Society of Civil Engineers (ASCE) (see the editorials by Sumer, 2006 and 2007). Those from SCARCOST were summarized in a paper in *Coastal Engineering* by Sumer *et al.* (2001).

The topic has continued to receive much attention, which has led to a substantial number of recent publications in journals and conference proceedings.

The present book intends (1) to collect state-of-the-art knowledge based on the above work, (2) to build content, and (3) to create interest in this currently popular area.

The primary aim of the book is to describe wave-induced liquefaction processes and their implications for marine structures. A clear hydrodynamic/geodynamic understanding makes it relatively easier for a consulting engineer to assess liquefaction potential, to make engineering predictions, and to make recommendations as to how to avoid potential risks. This book is essentially intended for professionals and researchers in the area of Coastal, Ocean and Marine Civil Engineering, and as a textbook for graduate/postgraduate students.

Soil liquefaction caused by earthquakes has been studied quite extensively in the past 30 years or so. This has culminated into a substantial body of literature, including books by Seed and Idriss (1982), Kramer (1996, Chapter 9), and most recently, Jefferies and Been (2006) and Idriss and Boulanger (2008). The application to port structures of soil liquefaction caused by earthquakes is covered in a book titled "Seismic Design Guidelines for Port Structures", published by PIANC (The World Association for Waterborne Transport Infrastructure) in 2001.

The present book differs from the aforementioned literature in the sense that it focuses on wave-induced liquefaction, although one chapter (Chapter 10) is devoted solely to the topic of earthquake-induced liquefaction and its implications for marine structures.

The author believes that the present book and the existing body of literature on seismic-induced liquefaction with special reference to marine structures form a complementary source of information on liquefaction around marine structures.

The author has interacted in his research on liquefaction with:

- Many colleagues: Professor Jørgen Fredsøe (Technical University of Denmark (DTU)), Professor Dong Jeng (University of Dundee, UK), Professor Liang Cheng (University of Western Australia), and colleagues from the LIMAS project (in alphabetical order): Mr. J. S. Damgaard (COWI, UAE), Mr. M. B. de Groot (GeoDelft, the Netherlands), Dr. S. Dunn (HR Wallingford, UK), Professor P. Foray (Domaine Universitaire, Grenoble, France), Dr. N.-E. O. Hansen (LICengineering, Denmark), Mr. M. Kudella (Technische Universitat Braunschweig, Germany), Professor M. Mory (University of Pau, France), Professor H. Oumeraci (Technische Universitat Braunschweig, Germany), Professor A. C. Palmer (University of Cambridge, UK, currently at National University of Singapore), Professor R. Sandven (NTNU, Norway), and Professor A. Sawicki (Inst. of Hydroengineering, Poland);

- Former research associates: Professor Nian-Sheng Cheng, Dr. Waldemar Magda, Dr. Figen Hatipoglu Dixen, Mr. S. Kaan Sumer, Dr. Abidin Kaya, and Dr. Ozgur Kirca; and

- Former students: Mr. Morten T. Lind, Mr. Steffen Christensen, Dr. Christoffer Truelsen, Mr. Søren Juhl Andersen and Mr. Jørgen Bang Jensen.

A draft of the manuscript was sent to Dr. Eng. Shinji Sassa (Head, Soil Dynamics Group, Geotechnical Engineering Field, Port and Airport Research Institute (PARI), Yokosuka, Japan), and Dr. Ozgur Kirca (Istanbul Technical University, Department of Civil Engineering) for their review and comments.

Dr. Sassa went through the entire manuscript, and provided the author with invaluable comments, which have been incorporated into the final version of the manuscript. The author is truly grateful to Dr. Sassa for this.

Dr. Kirca (who was a former postdoctoral research fellow with the author at DTU from 2009–2011) also went through the manuscript, and provided the author with equally invaluable comments. Dr. Kirca also produced excellent videos (shot during his stay at DTU) which are collected on the CD-ROM accompanying this book. The author is also truly grateful to Dr. Kirca for these.

The author would like to express his appreciation for the support of Professor Henrik Carlsen (Head, Department of Mechanical Engineering, DTU) and for the excellent working environment at DTU Mekanik. The author's thanks go also to Professor Jørgen Juncher Jensen (Head, Section for Fluid Mechanics, Coastal and Maritime Engineering, Department of Mechanical Engineering, DTU), who gave support to the author; to Mr. Henning Jespersen and Mr. Jan Larsson who skillfully provided technical assistance to the author and to his research associates and his students for the "endless" wave-induced liquefaction tests in the laboratory; and to Mr. Hans Jørn Poulsen, who prepared the figures for the book with patience and skill.

A significant part of the author's research on wave-induced liquefaction during the last 20 years has been supported by various research programs,

notably:

- "Scour Around Coastal Structures (SCARCOST)", 1997–2000, Contract No. MAS3-CT97-0097 of the Commission of the European Communities, Directorate-General XII for Science, Research and Development (Program Marine Science and Technology, MAST III);
- "Liquefaction Around Marine Structures (LIMAS)", 2001–2004, Contract No. EVK3-CT-2000-00038, of the same commission (FP5 specific program "Energy, Environment and Sustainable Development");
- "Exploitation and Protection of Coastal Zones (EPCOAST)", 2005–2007, Sagsnr. 26-00-014 of the Danish Research Agency, Danish Councils for Independent Research, The Danish Research Council for Technology and Production Sciences (FTP);
- "Seabed Wind Farm Interaction", 2008–2012, Sagsnr. 2104-07-0010 of the Danish Agency for Science Technology and Innovation, Danish Council for Strategic Research (DSF), Programme Commission on Energy and Environment; and
- "Innovative Multi-purpose Offshore Platforms: Planning, Design and Operation (MERMAID)", 2012–2016, Grant Agreement No. 288710 of the European Commission, 7th Framework Programme for Research.

The author has been the program leader of SCARCOST, LIMAS, EPCOAST, and Seabed Wind Farm Interaction.

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Contents

Chapter 1

Introduction and Physics of Liquefaction

1.1 Introduction

In geotechnical-engineering terminology, liquefaction refers to the state of the soil where the effective stresses between the individual grains vanish, and the water–sediment mixture as a whole, therefore, acts like a fluid. Under this condition, the soil fails, thus precipitating failure of the supported structure. Some such failures have been catastrophic. With the soil liquefied, buried pipelines may float to the surface of the seabed, pipelines laid on the seabed may sink (penetrating to greater depths), large individual blocks (like those used for scour protection) may penetrate into the seabed, sea mines may enter into the seabed and eventually disappear, and gravity structures (such as caisson breakwaters, offshore platforms, box caissons, etc.) may fail.

Marine soils that can be liquefied under wave action are basically limited to fine soils such as silt or fine sand, or, in composite soils, to silty sand, or clayey sand, as will be discussed in greater details later in the book. From Table B.1 in Appendix B, these kinds of soil components correspond to grain sizes $d = 0.074 - 0.4\,\mathrm{mm}$ (for fine sand), and $d < 0.074\,\mathrm{mm}$ (for silt).

Figs. 1.1 and 1.2 display distributions of sediments in the North Atlantic Ocean and in the North Pacific Ocean, respectively (Keller, 1967). As seen from these figures, these types of sediments, sand-silt and silt-clay, are almost invariably present in the areas where most marine and offshore construction takes place.

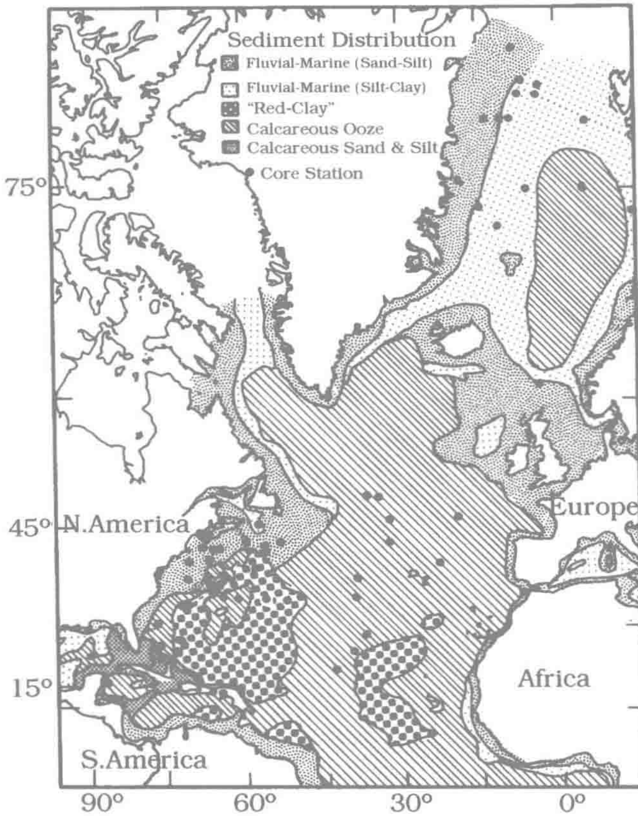

Figure 1.1: Distribution of sediments in the North Atlantic Ocean. Adapted from Keller (1967).

Table 1.1 gives examples of soil types (with corresponding grain sizes) in projects where the author has been involved as a consultant (a partial list). In these projects, either wave-induced liquefaction has occurred, or there has been large potential.

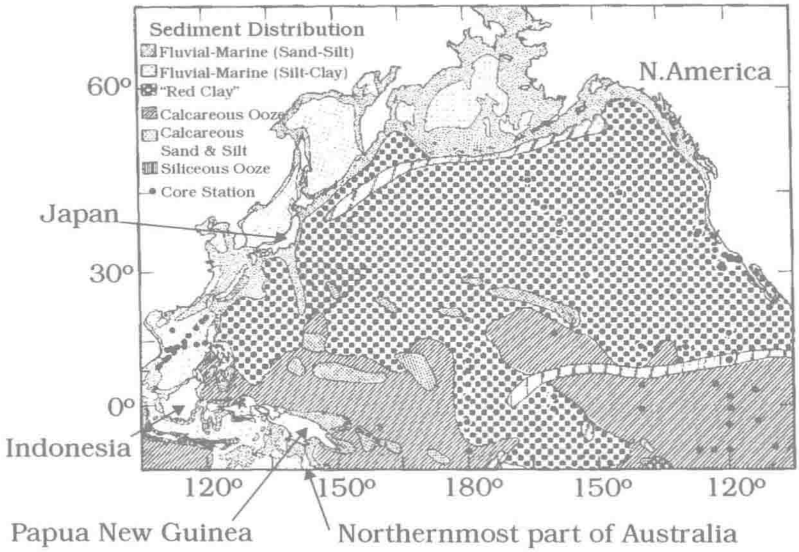

Figure 1.2: Distribution of sediments in the North Pacific Ocean. Adapted from Keller (1967).

Table 1.1. Examples of soil types taken from projects where either liquefaction has occurred, or where there has been large potential.

Location	Soil type	Grain size (mm)
Australia	Fine sand	0.135
Bangladesh	Fine sand	0.080
	Silt	0.003–0.070
Canada	Silty sand	0.050–0.150
Denmark	Fine sand	0.150
UK	Silty sand	0.080–0.120
	Silt	0.060–0.070

Several examples of liquefaction have been reported in the literature in conjunction with marine engineering.

Christian, Taylor, Yen and Erali (1974) and Herbich, Schiller, Dunlap and Watanabe (1984) report incidents where sections of pipelines floated to the surface of the soil during storms.

Floatation is just one of possible other consequences of the seabed liquefaction as far as pipelines are concerned. Fig. 1.3 illustrates various scenarios (Damgaard, Sumer, Teh, Palmer, Foray and Osario, 2006). Case (a) shows a pipeline that is lighter than the surrounding liquefied soil. In this case the pipeline will float to the surface of the seabed and become exposed to the wave and current forces, as well as to impacts from dropped objects, trawl collision, etc. Case (b) where the pipeline is heavier than the surrounding liquefied soil, is probably not very usual; normally the pipe weight will be reduced as much as possible to save on costs of construction and installation, but there are situations where other factors dictate a heavy pipeline. In this case the seabed liquefaction will cause the pipe to sink. Pipelines may, for various reasons, be protected by a rock cover (Sumer and Fredsøe, 2002). In that case seabed liquefaction can result in sinking of the rock cover (Case (c)). The fourth case (Case (d)) involves a bottom-seated pipeline designed to remain stable on the surface of the bed, assuming that the seabed itself will remain stable. If the seabed is liquefied before the pipeline stability is lost, then the pipeline will remain probably partially buried in the seabed, but exposed to the action of current and waves. This will cause large horizontal and vertical displacements of the pipeline.

Dunlap, Bryant, Williams and Suheyda (1979) describe storm-induced pore pressures in soft, clayey sediments in the Mississippi Delta where sinking of several of the measuring instruments up to 6–14 ft was noted.

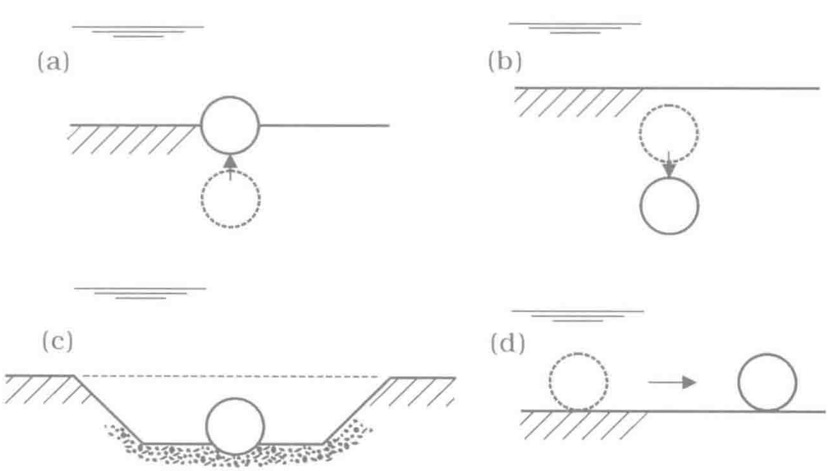

Figure 1.3: Possible consequences of liquefaction. Damgaard *et al.* (2006).