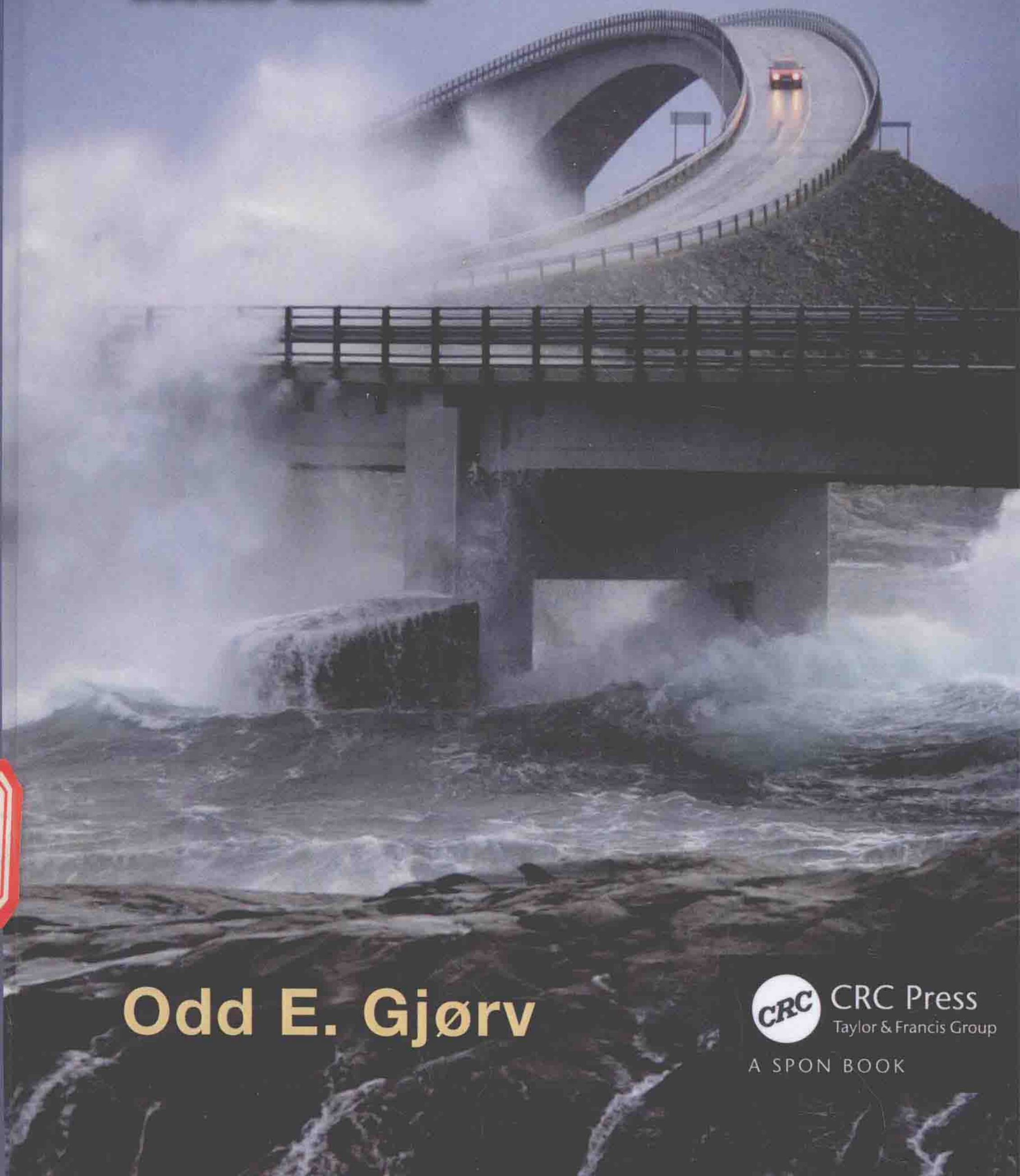
Durability Design of Concrete Structures in Severe Environments

Second Edition



Odd E. Gjørv

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Preface

Concrete structures in severe environments include a variety of structures in various types of environments. Although several deteriorating processes such as alkali–aggregate reactions, freezing and thawing, and chemical attack still represent severe challenges and problems to many important concrete structures, rapid development in concrete technology in recent years has made it easier to control such deteriorating processes. Also, for new concrete structures in severe environments, the applied concrete is normally so dense that concrete carbonation does not represent any practical problem. For concrete structures in chloride-containing environments, however, chloride ingress and premature corrosion of embedded steel still appear to be a most difficult and severe challenge to the durability and performance of many important concrete infrastructures. In recent years, there has also been a rapid increase in the use of de-icing salt and rapid development on concrete structures in marine environments.

In order to obtain increased and better control of chloride ingress and corrosion of embedded steel, improved procedures and specifications for proper combinations of concrete quality and concrete cover are very important. Upon completion of new concrete structures, however, the achieved construction quality typically shows high scatter and variability, and, in severe environments, any weaknesses and deficiencies will soon be revealed, whatever durability specifications and materials have been applied. Therefore, improved procedures for quality control and quality assurance during concrete construction are also very important.

To a certain extent, a probability approach to the durability design can accommodate the high scatter and variability. However, a numerical approach alone is not sufficient to ensure the durability. In order to obtain a more controlled and improved durability, it is also essential to specify performance-based durability requirements that can be verified and controlled for proper quality assurance during concrete construction. Documentation of achieved construction quality and compliance with the specified durability should be the keys to any rational approach to more controlled and increased durability and service life of concrete structures in severe environments. Better procedures for condition assessment and preventive maintenance should also be essential, and such procedures should help provide the ultimate basis for achieving more controlled durability and service life of concrete structures.

In recent years, an increased number of owners of concrete structures have realized that even small additional costs, in order to obtain an increased and more controlled durability beyond what is possible to reach based on current concrete codes and practice, have been shown to be a very good investment. However, increased and more controlled durability is not only a technical and economic issue, but also an increasingly more important environmental and sustainability issue. Although the present book is mostly concerned with increased and more controlled durability from a technical point of view, a brief introduction to life cycle costs and life cycle assessment is also included.

Acknowledgments

Throughout my work over a span of many years to develop increased and more controlled durability of new important concrete infrastructures, I acknowledge a number of my doctoral students from recent years who have been working with various aspects of concrete durability and contributed to parts of the procedures for both the durability design and the concrete quality control, as outlined and discussed in the present book. These people include Tiewei Zhang, Olaf Lahus, Arne Gussiås, Franz Pruckner, Liang Tong, Surafel Ketema Desta, Miguel Ferreira, Őskan Sengul, Guofei Liu, and Vemund Årskog.

I also thank the Norwegian Coast Directorate and the Norwegian Association for Harbor Engineers for very good research cooperation and support, and in particular I would like to thank Tore Lundestad and Roar Johansen for their great interest and encouragement in trying out and applying the new knowledge to new important concrete infrastructures in Norwegian harbors. As a result of this cooperation, recommendations and guidelines for new durable marine concrete infrastructures were developed and adopted by the Norwegian Association for Harbor Engineers in 2004. Lessons learned from practical applications of these recommendations and guidelines were incorporated into subsequent revised editions, the third and last of which, from 2009, was also adopted by the Norwegian Chapter of PIANC, which is the world association for waterborne transport infrastructure. These recommendations and guidelines are basically the same as those described in the present book, and the DURACON software that provides the basis for the durability analyses is also the same. This software can be freely downloaded from the home page of the Norwegian Chapter of PIANC (http://www.pianc.no/duracon.php).

In this second and revised edition of the current book, more results and experience from practical applications of the above procedures for durability design and concrete quality control applied to recent commercial projects, for both Oslo Harbor KF and Nye Tjuvholmen KS in Oslo, are included. The opportunity to publish all these results is greatly appreciated.

Some preliminary results from the more comprehensive NRF Research Program *Underwater Infrastructure and Underwater City of the Future* at Nanyang Technological University in Singapore are also included, which is greatly appreciated. In this program, the above procedures for durability design and concrete quality control have also been adopted as part of the technical basis for future development of Singapore City based on a large number of sea-spaced concrete structures.

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About the Author

Odd E. Gjørv, PhD, DrSc, is professor emeritus in the Department of Structural Engineering at the Norwegian University of Science and Technology (NTNU) in Trondheim, Norway. He joined the Faculty of Technology and Engineering at NTNU in 1971, where he introduced extensive teaching programs in concrete technology at both undergraduate and graduate levels. His teaching also included the supervision of a large number of MSc and PhD students majoring in concrete technology. As a visiting professor, Dr. Gjørv has taught at the University of California, Berkeley, and has given many invited lectures in several countries. He has been a member of the Norwegian Academy of Technical Sciences (NTVA) since 1979 and has participated in a large number of international professional activities and societies. He is currently engaged as an international collaborator on the NRF Research Program *Underwater Infrastructure and Underwater City of the Future* at Nanyang Technological University in Singapore.

Dr. Gjørv has published more than 350 scientific papers, 2 books, and has contributed to many other professional books. He has received several international awards and honors for his research. He has been a Fellow of the American Concrete Institute since 1989. From 1971 to 1995, he was continuously involved in the development and construction of all the offshore concrete platforms for oil and gas explorations in the North Sea. Dr. Gjørv's research includes advanced concrete materials and concrete construction as well as durability and performance of concrete structures in severe environments. He can be contacted through his website, http://folk.ntnu.no/gjorv/.

Contents

Chapter 1

Historical review

When Smeaton constructed the famous lighthouse on Eddystone Rock at the outlet of the English Channel during the period 1756–1759 (Smeaton, 1791), this was the first time a specially developed type of cement for a severe marine environment was applied (Lea, 1970). When the structure was demolished due to severe erosion of the underlying rock in 1877, this structure had remained in very good condition for more than 100 years. Since Smeaton reported his experience on the construction of this lighthouse (Figure 1.1), all the published literature on concrete in marine environments has made up a comprehensive and fascinating chapter in the long history of concrete technology. During the last 150 years, a number of professionals, committees, and national authorities have been engaged in this issue. Numerous papers have been presented to international conferences, such as the International Association for Testing Materials in Copenhagen (1909), New York (1912), and Amsterdam (1927); the Permanent International Association of Navigation Congresses (PIANC) in London (1923), Cairo (1926), Venice (1931), and Lisbon (1949); the International Union of Testing and Research Laboratories for Materials and Structures (RILEM) in Prague in 1961 and 1969; the RILEM-PIANC in Palermo in 1965; and the Fédération Internationale de la Précontrainte (FIP) in Tibilisi in 1972. Already in 1923, Atwood and Johnson (1924) had assembled a list of approximately 3000 references, and still, durability of concrete structures in marine environments continues to be the subject for research, discussion, and international conferences (Malhotra, 1980, 1988, 1996; Mehta, 1989, 1996; Sakai et al., 1995; Gjørv et al., 1998; Banthia et al., 2001; Oh et al., 2004; Toutlemonde et al., 2007; Castro-Borges et al., 2010; Li et al., 2013).

In all this literature, the various deteriorating processes that may affect the durability and performance of concrete structures in severe environments have been extensively reported and discussed. Although a number of deteriorating processes such as alkali–aggregate reactions, freezing and thawing, as well as chemical attack still represent a severe challenge and potential threat to many concrete structures, it is not the disintegration of the concrete itself, but rather chloride-induced corrosion of embedded steel, A

NARRATIVE OF THE BUILDING

AND

A DESCRIPTION of the CONSTRUCTION

OF THE

EDYSTONE LIGHTHOUSE

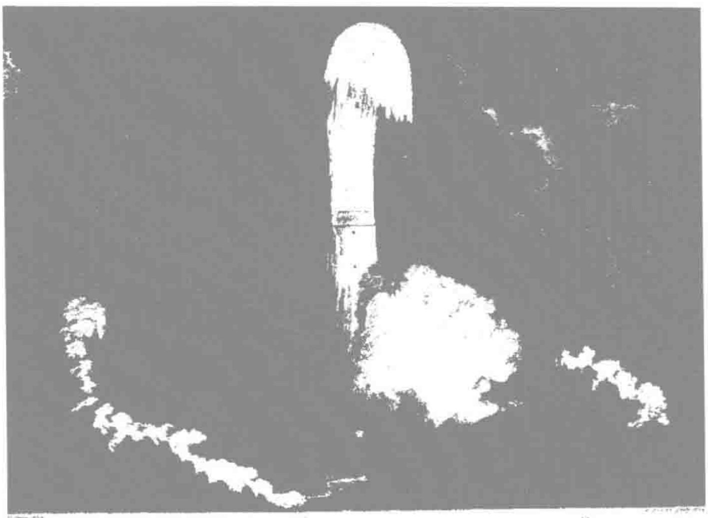
WITH STONE:

TO WHICH IS SUBJOINED,

AN APPENDIX, giving fome Account of the LIGHTHOUSE on the SPURN POINT,

BUILT UPON A SAND.

BY JOHN SMEATON, *CIVIL ENGINEER*, F.R.S.



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SOLD BY G. NICOL,

BOOKSELLER TO HIS MAJESTY, PALL-MALL. 1791.

Figure 1.1 Front page of the report on the construction of the Eddystone Lighthouse, written by John Smeaton in 1791. (Courtesy of the British Museum.)

that appears to be the most severe and greatest threat to the durability and performance of many important concrete structures. Already in 1917, the problem with corrosion of embedded steel was pointed out by Wig and Ferguson (1917) after a comprehensive survey of concrete structures in U.S. waters.

In addition to conventional structures such as bridges and harbor structures, reinforced and prestressed concrete has already, for a long time, been increasingly applied to a large number of very important ocean structures and vessels. Of the total surface area of the globe, ocean water makes up about 70%, and the inhabitable part of the remaining area is even smaller and is becoming increasingly more populated. Since the need for more space, raw materials, and transportation is steadily increasing, increasingly more activities are being moved into ocean waters and marine environments.

Already in the early 1970s, the American Concrete Institute (ACI) came up with a technological forecasting on the future use of concrete, where the rapid development on the continental shelves was pointed out (ACI, 1972). In this report not only structures related to oil and gas explorations but also structures that would relieve land congestion were discussed.

At an international FIP Symposium on Concrete Sea Structures organized by Gosstroy in Tbilisi in 1972 (Gosstroy, 1972), a great variety of concrete structures that would play an increasing role for further activities in ocean and marine environments were discussed. Such structures would be of different types and categories, such as

- Nonanchored freely floating structures, e.g., ships, barges, and containers
- Anchored structures floating at water surface level, e.g., bridges, dry docks, operation platforms, moorings, nuclear plants, airports, and cities
- Anchored structures (positive buoyancy) floating below surface level, e.g., tunnels
- Bottom-supported structures (negative buoyancy) resting above seabed level, e.g., tunnels and storage units
- Bottom-supported structures (negative buoyancy) resting at or below seabed level, e.g., bridges, harbor structures, tunnels, storage units, caissons, operation platforms, as well as both tidal and nuclear power plants

The ACI forecasting pointed out the great potential for utilization of concrete as a construction material for marine and ocean applications in general and for offshore oil and gas exploration in particular. In Norway, where most of the offshore concrete construction has taken place so far, long traditions have existed on the utilization of concrete in the marine environment. Already in the early 1900s, the two Norwegian engineers Gundersen and Hoff developed and obtained a patent on the tremie method for underwater placing of concrete during the construction of the Detroit River Tunnel between the United States and Canada (Gjørv, 1968). From 1910, when

Figure 1.2 Open concrete structures are still the most common type of harbor structures built along the Norwegian coastline.

Gundersen came back to Norway and became the director of the new contracting company AS Høyer-Ellefsen, his newly patented method for underwater placement of concrete became the basis for the construction of a new generation of piers and harbor structures all along the rocky shore of the Norwegian coastline (Gjørv, 1968, 1970). These structures typically consist of an open reinforced concrete deck on top of slender, reinforced concrete pillars cast under water. Although the underwater cast concrete pillars were gradually replaced by driven steel tubes filled with concrete, this open type of concrete structure is still the most common type of harbor structure being constructed along the Norwegian coastline (Figure 1.2).

Due to its very long and broken coastline with many fjords and numerous inhabited islands, Norway has a long tradition on the use of concrete as a construction material in marine environments (Figure 1.3). For many years, this primarily included concrete harbor structures. Gradually, however, concrete also played an increasing role as a construction material for other applications, such as strait crossings (Klinge, 1986; Krokeborg, 1990, 1994, 2001). In addition to conventional bridges (Figure 1.4), new concepts for strait crossings such as floating bridges (Figure 1.5 and 1.6) emerged (Meaas et al., 1994; Hasselø, 2001). Even submerged concrete tunnels have been the subject for detailed studies and planning; one of several types of design is shown in Figure 1.7 (Remseth, 1997; Remseth et al., 1999).

The rapid development that later took place on the utilization of concrete for offshore installations in the North Sea is well known (Figures 1.8 and 1.9). Thus, since 1973, altogether 34 major concrete structures containing more than 2.6 million m^3 of high-performance concrete were installed (Figure 1.10), most of which were produced in Norway. Also in other parts of the world, a number of offshore concrete structures have been produced in recent years, and so far, a total of 50 various types of offshore concrete structures have been installed (Moksnes, 2007).