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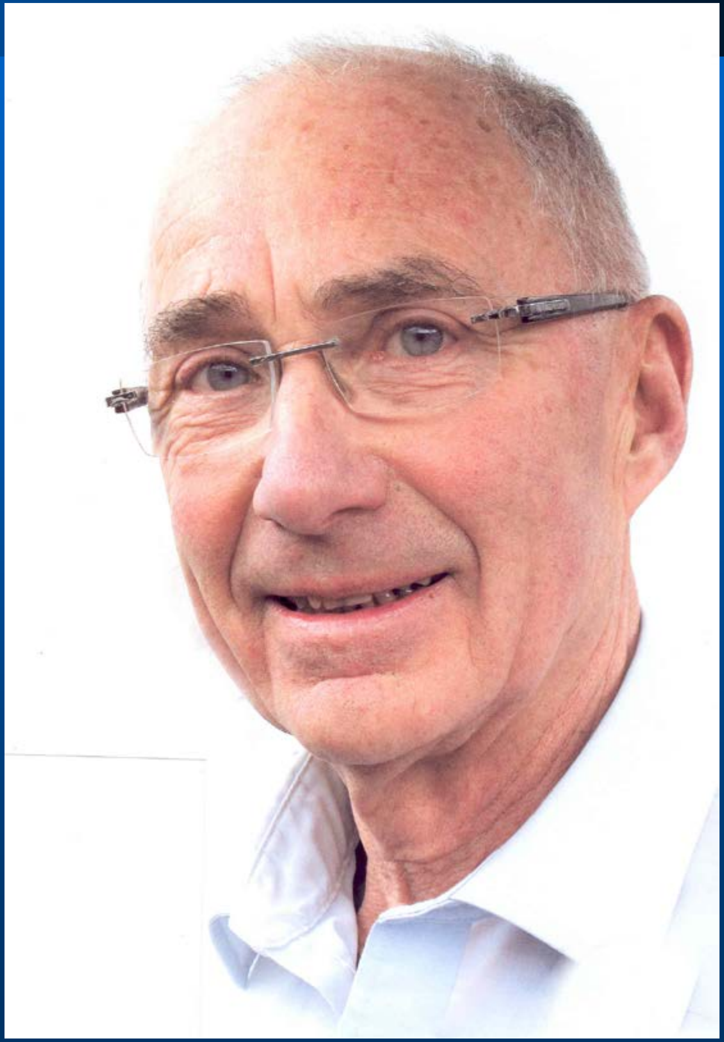


Durability Design and Quality Assurance of Major Concrete Infrastructure

DURABILITY OF CONCRETE STRUCTURES IN SEVERE ENVIRONMENTS

- *Design*
- *Materials*
- *Construction*

Field experience

Much of the observed durability problems can be ascribed due to lack of proper quality assurance during concrete construction and poorly achieved construction quality

Field experience (cont.)

Upon completion of new concrete structures, the achieved construction quality generally shows a high scatter and variability

Field experience (cont.)

During operation of the concrete structures, any weaknesses and deficiences will soon be revealed whatever durability specifications and materials have been applied

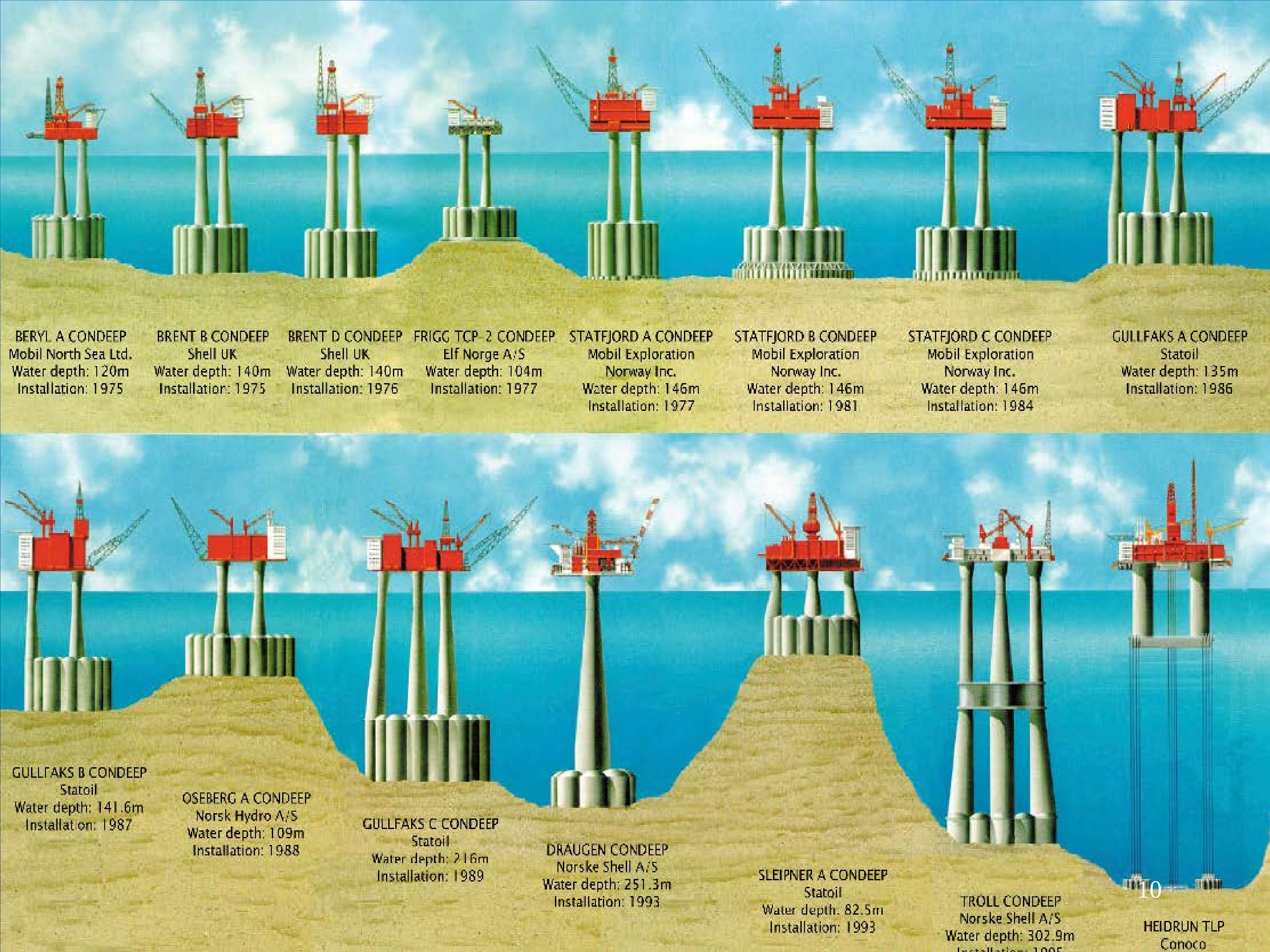
Field experience (cont.)

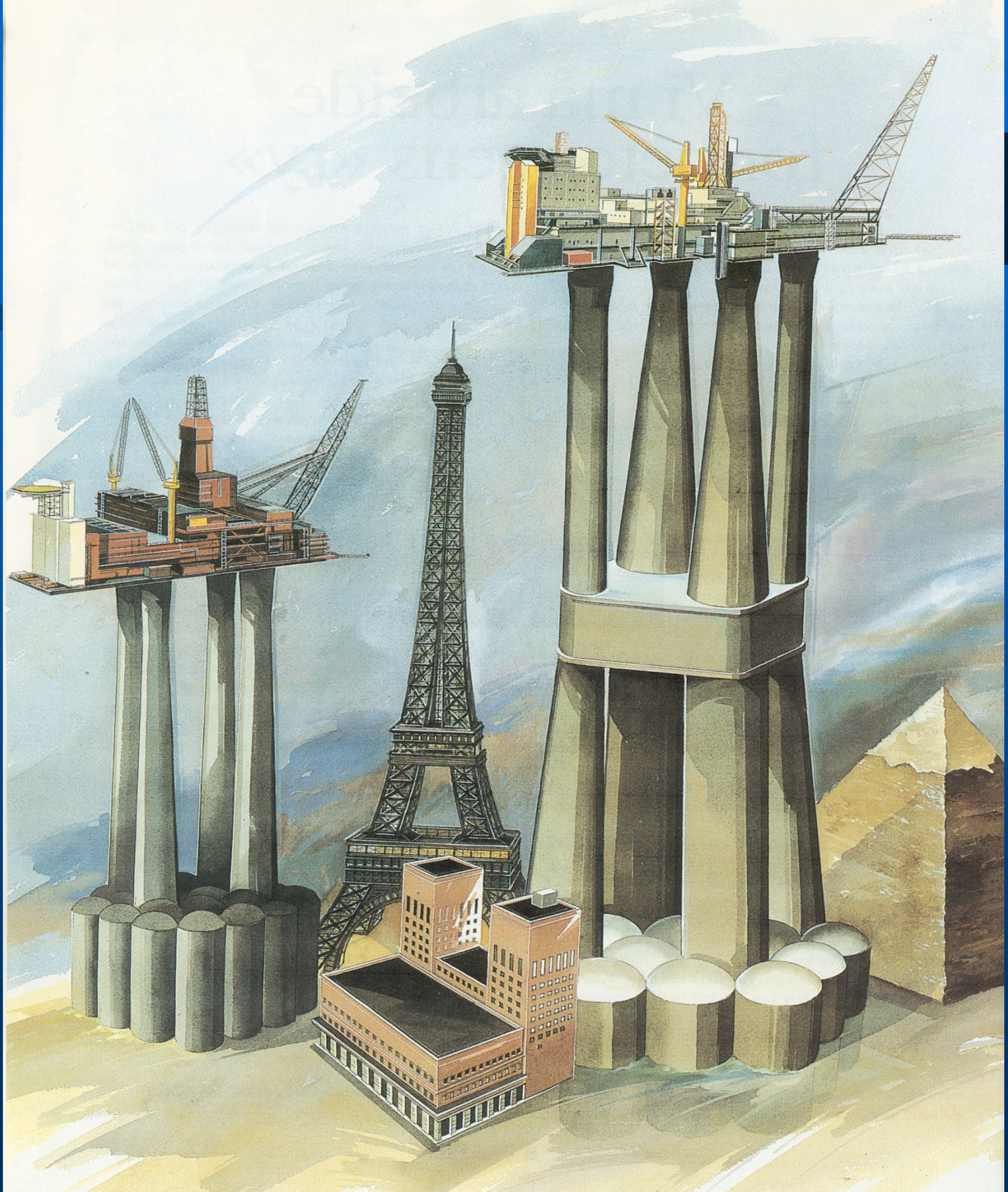
In severe environments, most of the durability problems can be ascribed due to an uncontrolled ingress of chlorides with subsequent corrosion of embedded steel

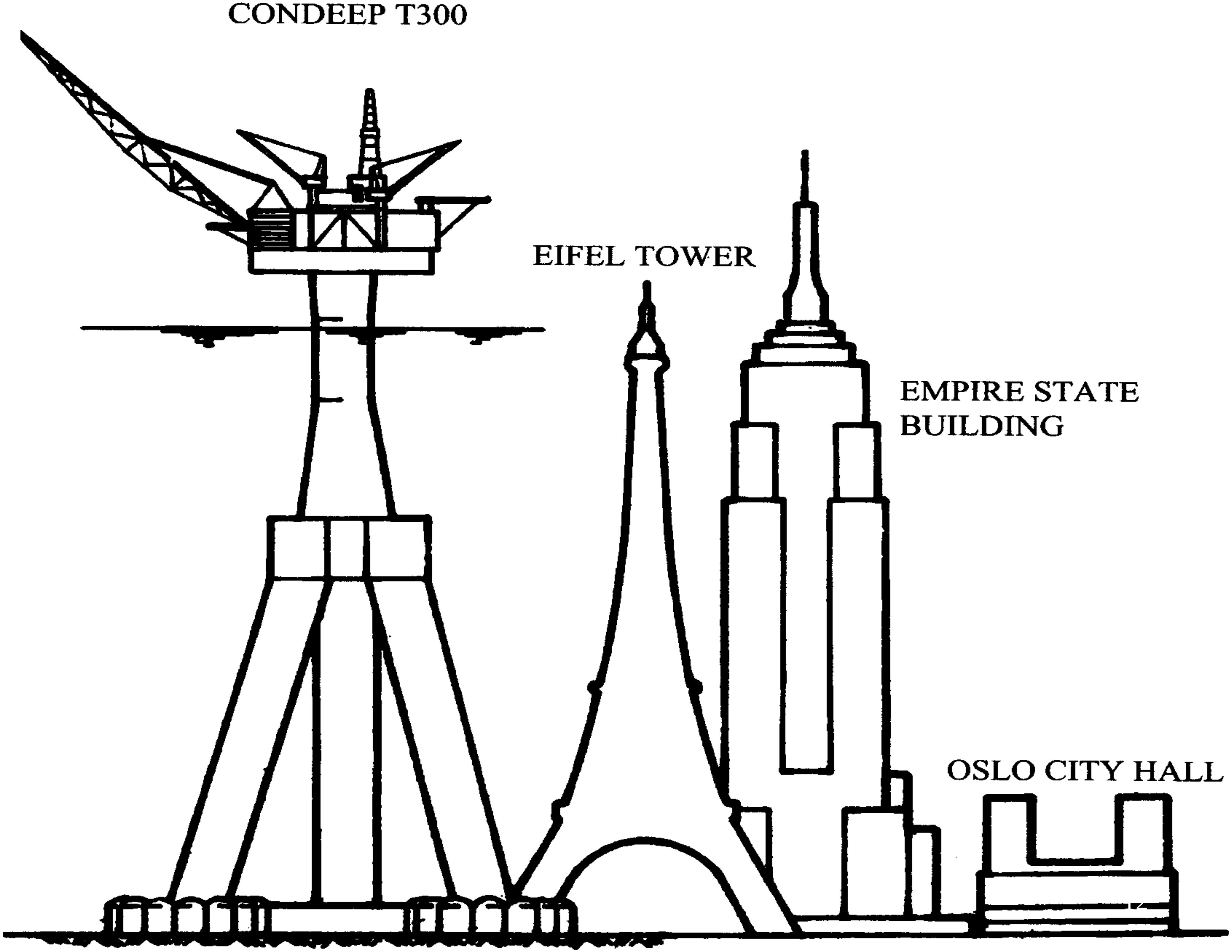
Concrete platforms in the North Sea

Since the early 1970s, 34 offshore concrete platforms were produced for the oil and gas explorations in the North Sea


PACIFIC
SIMSON


BERYL A CONDEEP
Mobil North Sea Ltd.
Water depth: 120m
Installation: 1975
BRENT B CONDEEP
Shell UK
Water depth: 140m
Installation: 1975
BRENT D CONDEEP
Shell UK
Water depth: 140m
Installation: 1976
FRIGG TCP-2 CONDEEP
Elf Norge A/S
Water depth: 104m
Installation: 1977
STATFJORD A CONDEEP
Mobil Exploration
Norway Inc.
Water depth: 146m
Installation: 1977
STATFJORD B CONDEEP
Mobil Exploration
Norway Inc.
Water depth: 146m
Installation: 1981
STATFJORD C CONDEEP
Mobil Exploration
Norway Inc.
Water depth: 146m
Installation: 1984
GULLFAKS A CONDEEP
Statoil
Water depth: 135m
Installation: 1986
GULLFAKS B CONDEEP
Statoil
Water depth: 141.6m
Installation: 1987
OSEBERG A CONDEEP
Norsk Hydro A/S
Water depth: 109m
Installation: 1988
GULLFAKS C CONDEEP
Statoil
Water depth: 216m
Installation: 1989
DRAUGEN CONDEEP
Norske Shell A/S
Water depth: 251.3m
Installation: 1993
SLEIPNER A CONDEEP
Statoil
Water depth: 82.5m
Installation: 1993
TROLL CONDEEP
Norske Shell A/S
Water depth: 302.9m
Installation: 1995
HEIDRUN TLP
Conoco




CONDEEP T300
EIFEL TOWER
EMPIRE STATE BUILDING
OSLO CITY HALL


25/1-FRIGG
TCP2

Concrete platforms in the North Sea (cont.)

For all the offshore concrete structures, the strictest durability requirements were specified and the strictest concrete quality control during concrete construction was applied

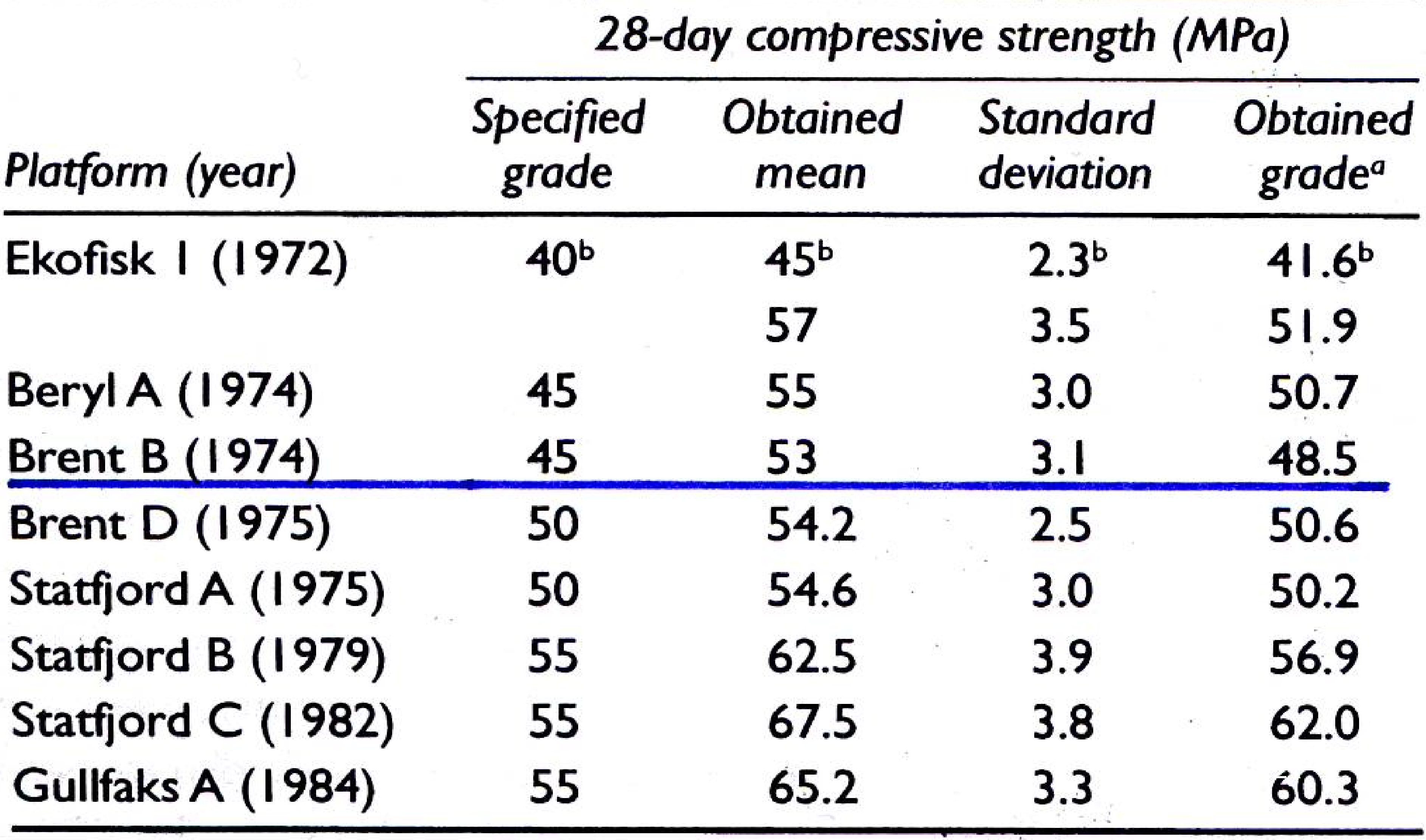
Concrete platforms in the North Sea (cont.)

Although the durability of the offshore concrete platforms has generally been much better than that of other marine concrete structures produced during the same period, also some of these concrete structures have shown very serious and costly durability problems

”Oseberg A Platform” (1988)

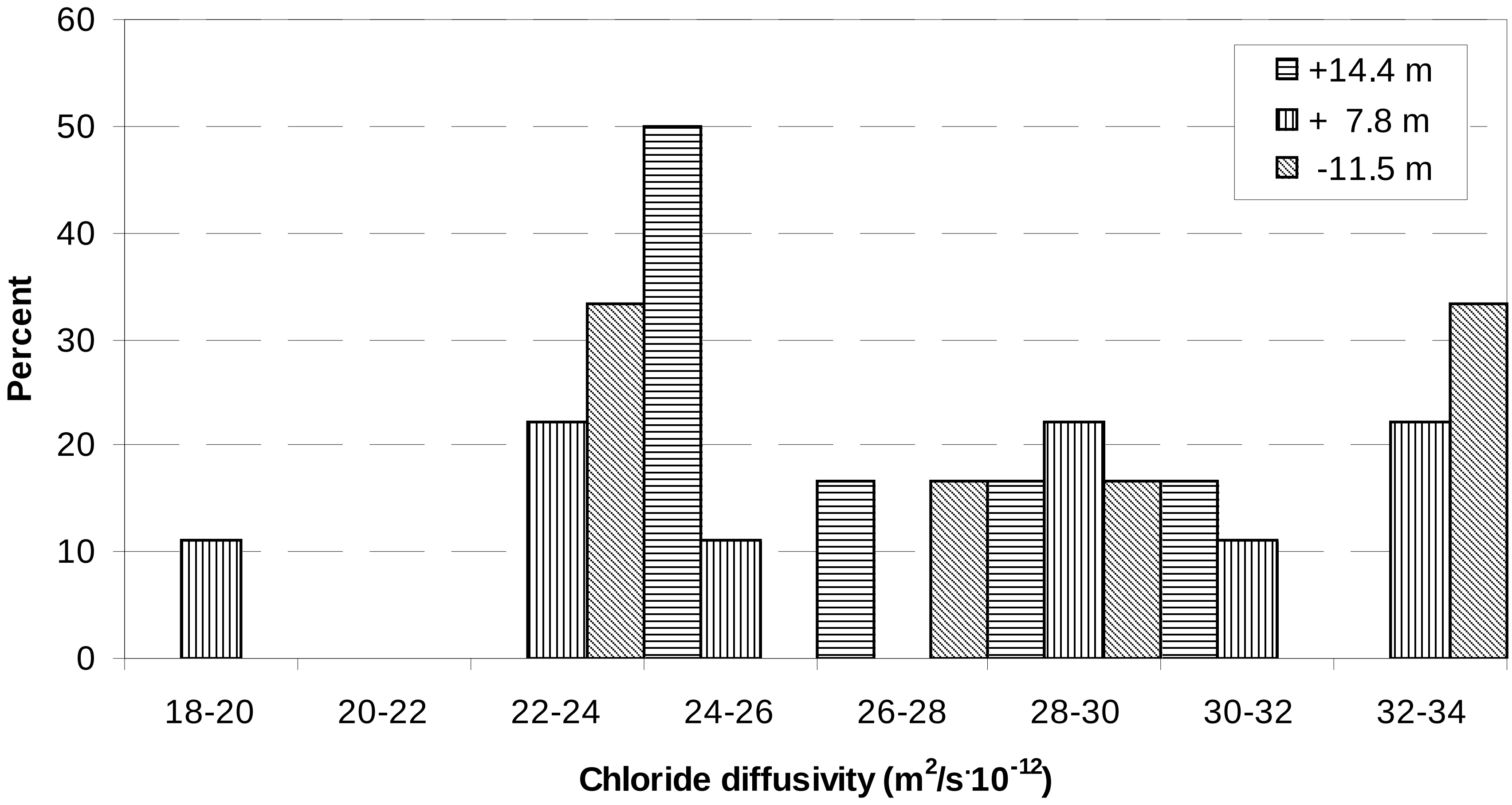
”Oseberg A Platform” (1988): Repairs after 13 years (CP)

Concrete quality control: 1972-84



Platform (year)	28-day compressive strength (MPa)			
	Specified grade	Obtained mean	Standard deviation	Obtained grade[a]
Ekofisk I (1972)	40[b]	45[b]	2.3[b]	41.6[b]
		57	3.5	51.9
Beryl A (1974)	45	55	3.0	50.7
Brent B (1974)	45	53	3.1	48.5
Brent D (1975)	50	54.2	2.5	50.6
Statfjord A (1975)	50	54.6	3.0	50.2
Statfjord B (1979)	55	62.5	3.9	56.9
Statfjord C (1982)	55	67.5	3.8	62.0
Gullfaks A (1984)	55	65.2	3.3	60.3

”Brent B Platform” (1975) Chloride diffusivity (RCM)



How to ensure that the specified durability is achieved?

To a certain extent, a probability approach to the durability design can accomodate the high scatter and variability

How to ensure that the specified durability is achieved? (cont.)

A nummerical approach alone is insufficient; performance-based durability requirements which can be verified and controlled during concrete construction are also essential

How to ensure that the specified durability is achieved? (cont.)

Proper quality assurance with documentation of achieved construction quality and complience to the durability specification should be essential parts of any rational approach to a more controlled and increased durability

How to control and improve the service life ?

For a more controlled and increased service life, regular condition assessment and preventive maintenance during operation of the structures are also essential

Design and execution of new concrete infrastructure

- All minimum requirements in existing concrete codes and standards must be strictly followed

Design and execution of new concrete infrastructure (cont.)

- **All established recommendations and guidelines for good construction practice must also be strictly followed**

(Cfr. CIRIA: ”The use of concrete in maritime engineering – *a good practice guide*”, London, 2010, 363 p.)

New research and development

In recent years, a rapid international research and development of new knowledge and experience on concrete durability has taken place:

- ***Probability-approach to the durability design***
- ***Performance-based durability requirements***

Existing codes and standards

- Compared to the rapid development of new knowledge and experience on concrete durability, existing concrete codes and practice have shown a very slow upgrading

Existing codes and standards (cont.)

- It has taken more than 30 years for the European Concrete Standards to reach the same strict durability requirements for marine concrete structures as that specified for the first offshore concrete structures in the North Sea in the early 1970s

Existing codes and standards (cont.)

- Although the required service life for the offshore concrete structures was much shorter, the international oil and gas industry was much more demanding in their requirements for obtaining a more safe and regular operation of their installations

Existing codes and standards (cont.)

- After more than 40 years of experience, the offshore concrete structures have shown a much better durability than that of other marine concrete structures produced during the same period

Exisiting codes and standards (cont.)

- However, also the offshore concrete structures have typically shown a high scatter and variability of achieved construction quality

Exisiting codes and standards (cont.)

- Also for some of the offshore concrete structures, very serious durability problems have occurred and very costly repairs carried out

Exisiting codes and standards (cont.)

- Both for the offshore and other concrete structures, the durability specifications have mainly been descriptive, the results of which are neither unique nor possible to verify and control for quality assurance during concrete construction

Repairs and maintenance costs

- In recent years, many owners of major concrete infrastructure have experienced that a significant and rapidly increasing proportion of their limited construction budgets are being spent on repairs and maintenance of existing concrete infrastructure

International challenge

- Annual bridge repairs in the USA
  - 1986: US$ mill. 500
  - 2001: US$ bill. 8.3
  - 2007: US$ bill. 9.4

Annual bridge repairs in Western Europe in 1998: US$ bill. 5

International challenge (cont.)

- A more controlled and increased durability and service life of new concrete infrastructure are not only important from a cost point of view; it directly affects the sustainability of our society

ADDITIONAL RERQUIREMENTS FOR A MORE CONTROLLED AND INCREASED DURABILITY AND SERVICE LIFE

- More and more owners are showing an increasing interest to invest somewhat more in order to obtain a more controlled and increased durability and service life beyond what is possible when only based on existing concrete codes and practice

ADDITIONAL RERQUIREMENTS FOR A MORE CONTROLLED AND INCREASED DURABILITY AND SERVICE LIFE (cont.)

- **In the newly published book, some additional requirements to existing concrete codes and practice for obtaining a more controlled and increased durability and service life of new major concrete infrastructure are recommended**

ADDITIONAL RERQUIREMENTS FOR A MORE CONTROLLED AND INCREASED DURABILITY AND SERVICE LIFE (cont.)

(1) An overall durability requirement to the given concrete structure should be specified, which is possible to verify and control for proper quality assurance during concrete construction

ADDITIONAL RERQUIREMENTS FOR A MORE CONTROLLED AND INCREASED DURABILITY AND SERVICE LIFE (cont.)

(2) Upon completion of the project, documentation of achieved construction quality and compliance with the durability specification should be required before the structure is formally handed over from the contractor

ADDITIONAL RERQUIREMENTS FOR A MORE CONTROLLED AND INCREASED DURABILITY AND SERVICE LIFE (cont.)

(3) Upon completion of the project, a service manual for future condition assessment and preventive maintenance of the structure should also be required

ADDITIONAL RERQUIREMENTS FOR A MORE CONTROLLED AND INCREASED DURABILITY AND SERVICE LIFE (cont.)

(1) Durability design

(2) Quality assurance and achieved construction quality

(3) Condition assessment and preventive maintenance

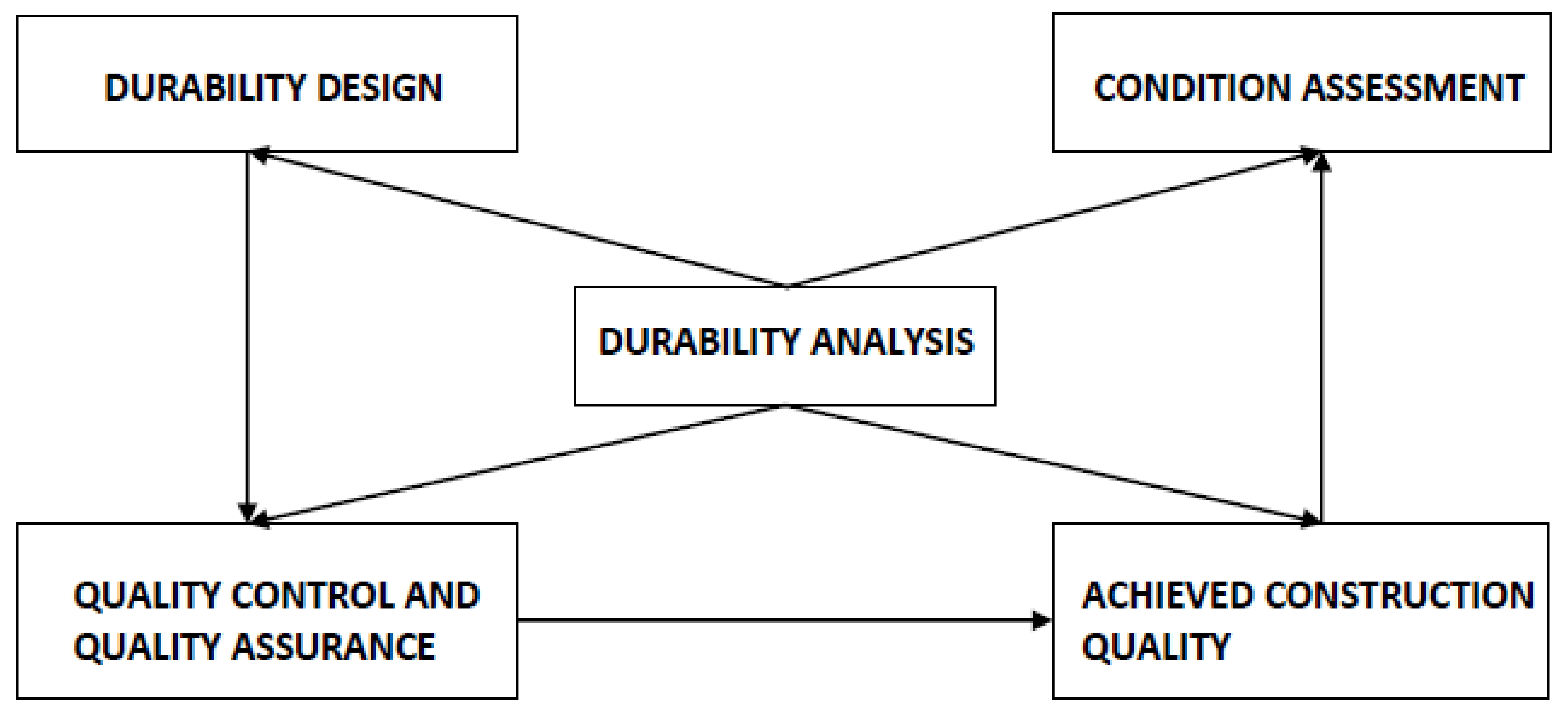
(1) DURABILITY DESIGN

Probability-based approach

***The probability-approach is based on a numerical model and established software, such as*:**

- **DURACON Model (DuraCrete)**
- **STADIUM Model**
- **Life 365-Model**

DURACON Model



DURABILITY DESIGN

CONDITION ASSESSMENT

DURABILITY ANALYSIS

QUALITY CONTROL AND QUALITY ASSURANCE

ACHIEVED CONSTRUCTION QUALITY

DURACON Model
Durability requirement

For the given concrete structure in the given environment, a certain ”Service period” before the probability of steel corrosion exceeds 10% (SL) is specified

DURACON Model
Durability analysis

The calculation of corrosion probability (durability analysis) is based on a simple combination of a modified Fick´s 2. Law of Diffusion and a Monte Carlo Simulation

DURACON Model
Durability analysis (cont.)

As a result of the durability analysis, requirements to concrete quality (RCM-chloride diffusivity) and concrete cover are established

(2) QUALITY ASSURANCE AND ACHIEVED CONSTRUCTION QUALITY

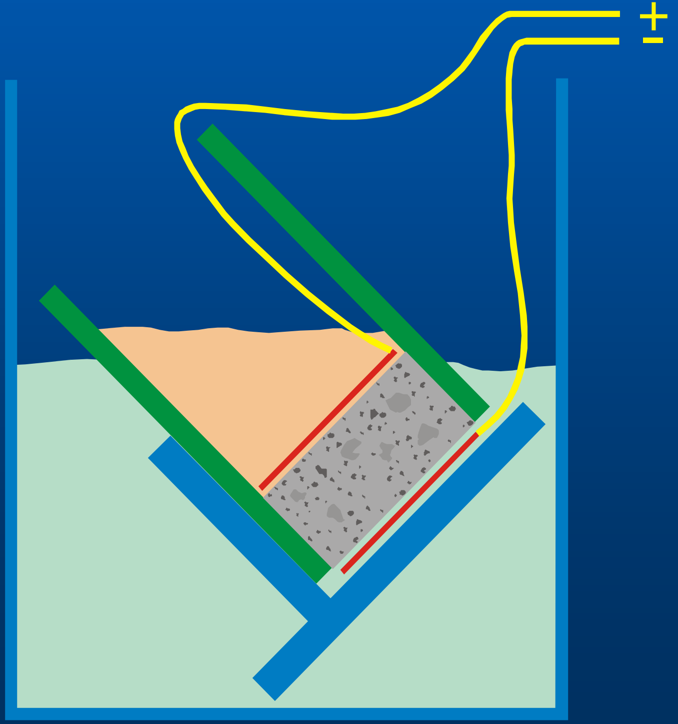
Performance-based concrete quality control

Ongoing control during concrete construction:

- *Chloride diffusivity* (D_{28})
- *Concrete cover (X)*

Testing of chloride diffusivity

Rapid chloride migration testing (RCM) (AASHTO TP 64-03; GB/T 50082)



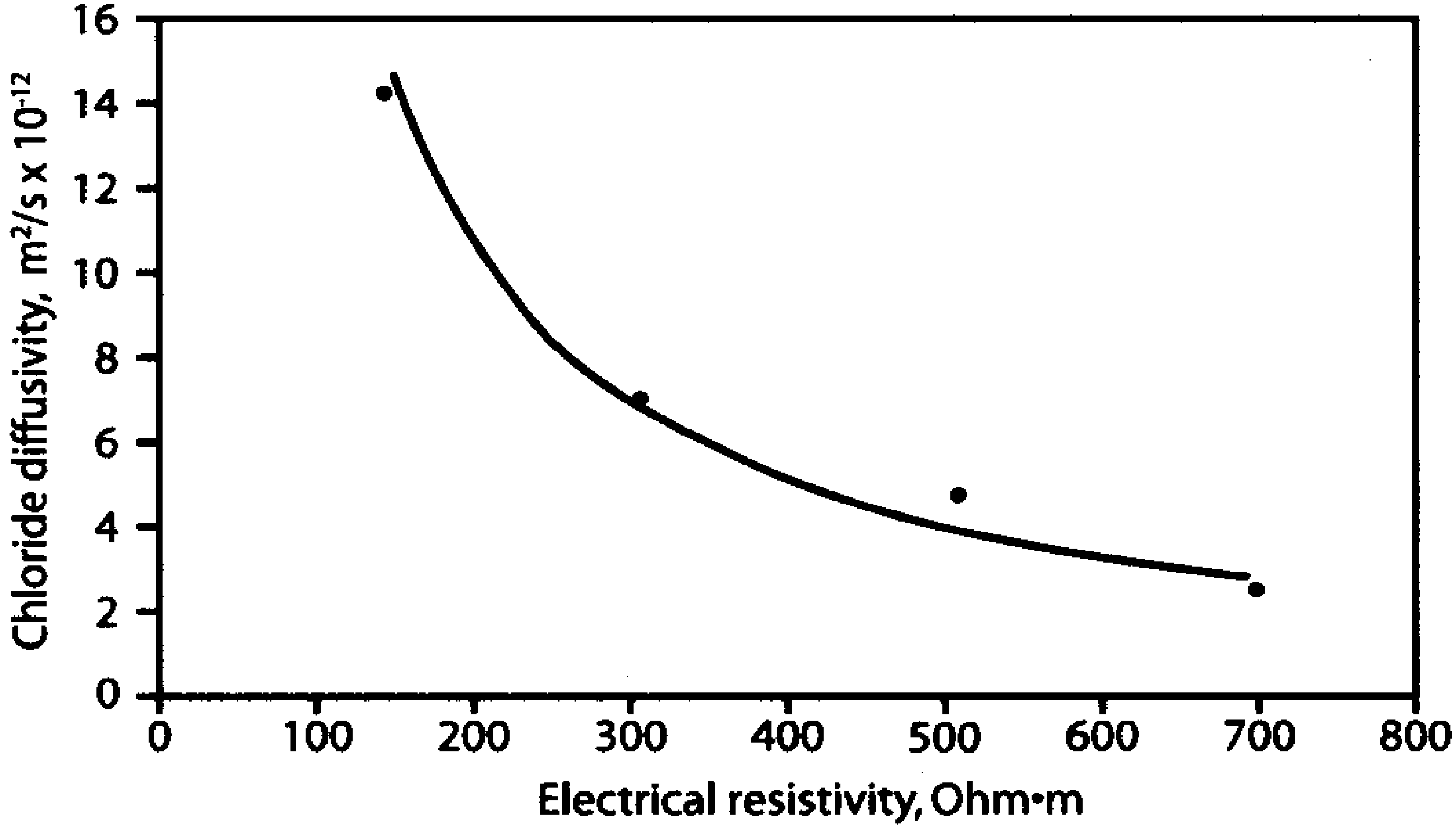
Relationship between diffusivity and electrical resistivity

Nernst-Einstein:

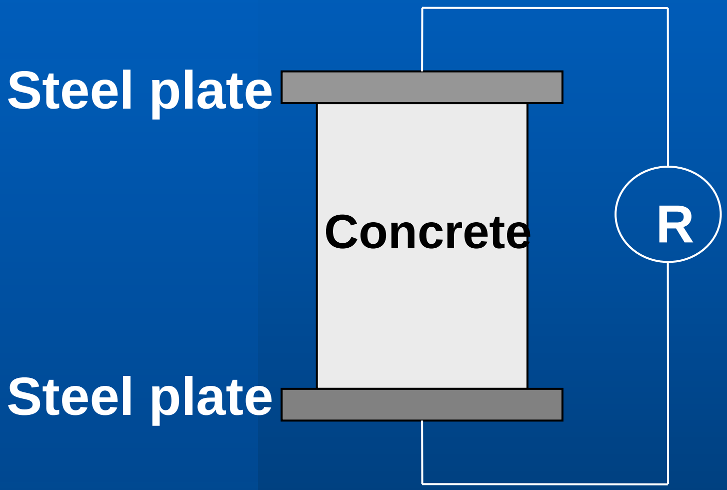
$$D = \frac{R.T}{Z^2.F^2} \cdot \frac{t_i}{\gamma_i.c_i.\rho}$$

$$D = k \cdot \frac{1}{\rho}$$

Calibration curve



Control of the electrical resistivity based on the 2-electrode method



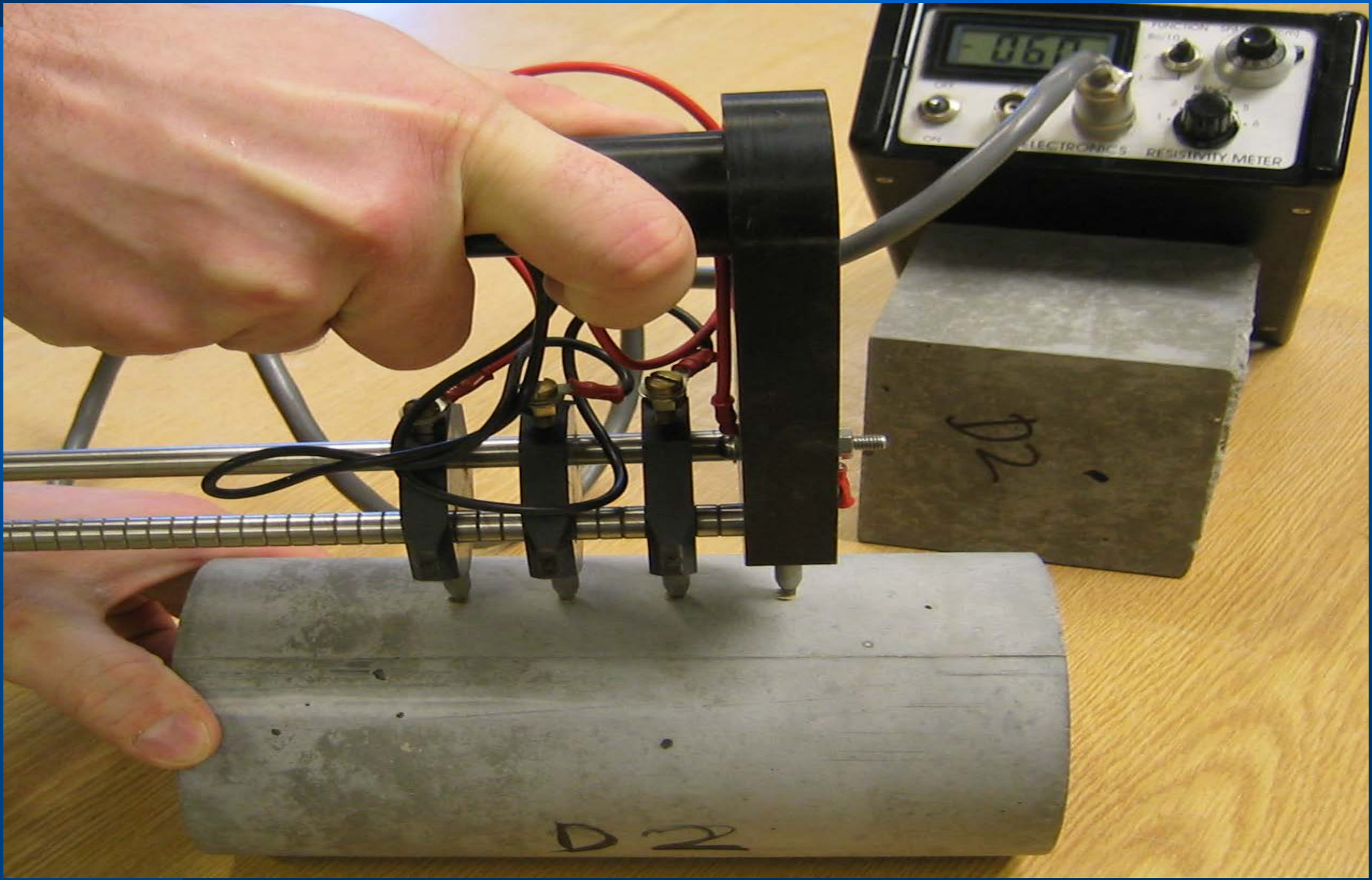
Steel plate

Concrete

R

Steel plate

Control of the electrical resistivity based on the 4-electrode method



Control of the 28-day chloride diffusivity (D_{28})

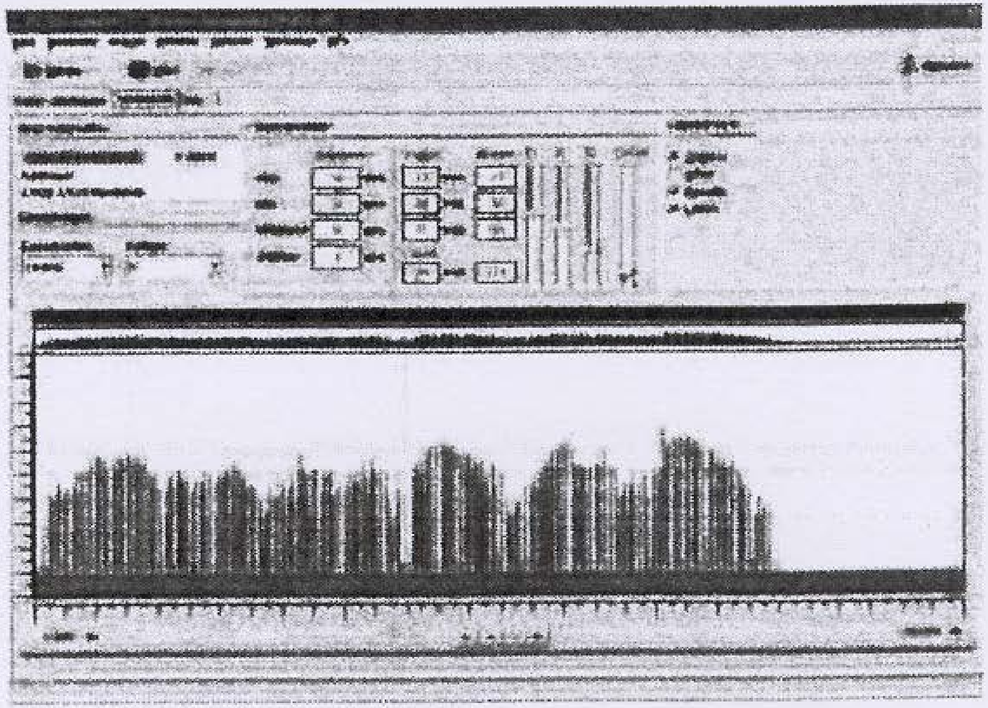
The ongoing control of the 28-day chloride diffusivity (D_{28}) is carried out indirectly by an ongoing testing of the electrical resistivity of the concrete

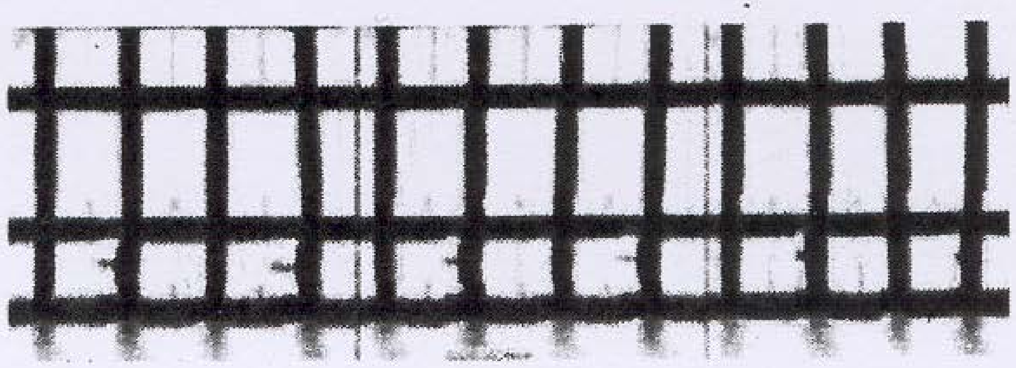
Control of the 28-day electrical resistivity

The ongoing control of the 28-day electrical resistivity is carried out on the same test specimens as that for control of the 28-day compressive strength

Control of concrete cover

Scanning equipment





Construction joints

Compliance with durability specification

Based on the obtained control data on both chloride diffusivity (D_{28}) and concrete cover (X) as input parameters to a new durability analysis, documentation of compliance with the durability specification is obtained

In-situ construction quality

New durability analysis:

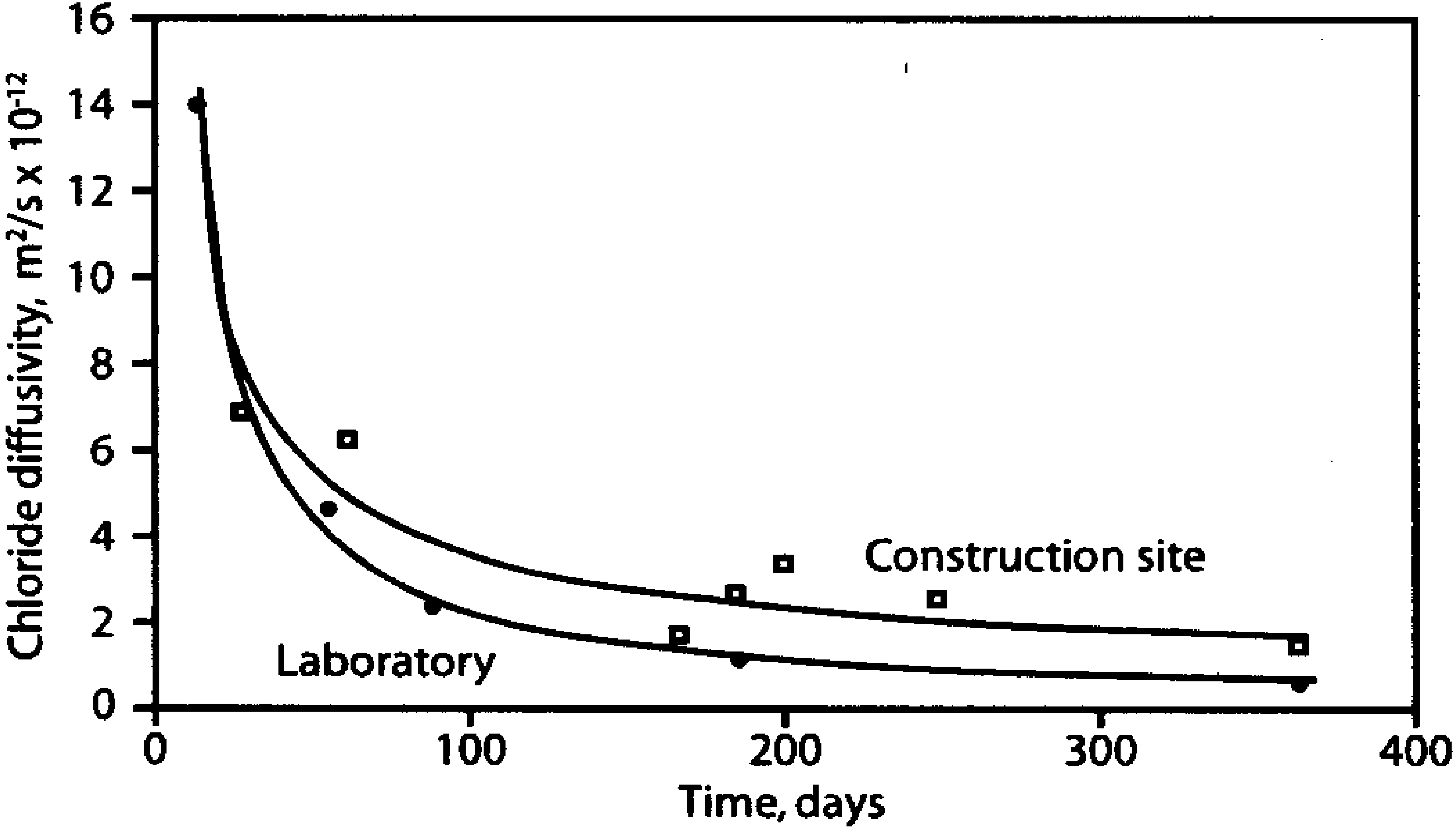
- Achieved in-situ chloride diffusivity based on testing of concrete cores from the given structure during the construction period
- Achieved concrete cover

Potential construction quality

New durability analysis:

- Potential chloride diffusivity based on testing of concrete specimens under controlled laboratory conditions during the construction period
- Achieved concrete cover

Development of chloride diffusivity



Achieved construction quality

Durability analyses based on achieved chloride diffusivities and concrete cover:

(1) ***Compliance with specified durability***

(2) ***In-situ construction quality***

(3) ***Potential construction quality***

(3) CONDITION ASSESSMENT AND PREVENTIVE MAINTENANCE

Control of future chloride ingress

Even if the strictest durability requirements both have been specified and achieved, a certain rate of chloride ingress will allways take place during operation of concrete structures in the marine environment

Control of future chloride ingress (cont.)

Regular monitoring of the real chloride ingress during operation of the concrete structure

Probability of corrosion

Calculations of corrosion probability based on observed chloride diffusivities (D_a) in combination with control data on concrete cover (X)

Probability of corrosion (cont.)

Before the probability of corrosion becomes too high, appropriate protective measures measures must be implemented

PRACTICAL APPLICATIONS

For several years, the DURACON Model has been applied for durability design and quality assurance of a large number of new major concrete structures

Container Terminal 1, Oslo (2002),

Container Terminal 2, Oslo (2007)

Container Terminal 2, Oslo (2015)

”New City Development: Tjuvholmen”, Oslo (2005-14)

”New City Development: Tjuvholmen”, Oslo

”New City Development: Tjuvholmen”, Oslo (2005-14)

Owner´s durability requirements:

(1) *”Service life” of 300 years*

(2) *Documentation of achieved construction quality (DURACON)*

”New City Development: Tjuvholmen” Oslo (2005-14)

The project included a number of concrete substructures in seawater:

- In-situ cast concrete structures for shallow water
- Prefabricated concrete caisons for deep water

In-situ cast structures

Prefabricated structures (dry dock)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Execution of work

The whole project was carried out in two parts by two different contractors (A and B) having two different strategies and approaches to the durability and service life of the structures

Contractor A:

- ***Probability-based durability design (DURACON)***
- ***Concrete structures No. 1 - 4***

Contractor B: Descriptive durability requirements

- *Current European Concrete Standards (NS-EN 206-1, 2003) + some additional requirements*
- *Concrete structures No. 5 - 8*

SUMMARY

(1) *Probability-based durability design:*

- It was possible to design a very good technical solution for the durability of the given concrete structures in the given environment during the required period of service

SUMMARY (cont.)

(2) ***Probability-based durability design:***

- **For the durability design, it was possible to accomodate the high scatter and variability of all input parameters**

SUMMARY (cont.)

(3) ***Probability-based durability design:***

- **It was possible to quantify how much of the black steel which was necessary to replace by stainless steel**

SUMMARY (cont.)

(4) ***Probability-based durability design:***

- **It was possible to quantify the performance-based durability requirements:**
  - ***28-day chloride diffusivity (D_{28})***
  - ***Concrete cover (X)***

SUMMARY (cont.)

(5) *Performance-based durability requirements:*

- **It was possible to detect and correct possible deviations in both D_{28} and X during concrete construction; reduced scatter and variability of achieved construction quality were typically observed**

SUMMARY (cont.)

(6) ***Performance-based durability requirements:***

- It was possible to document achieved construction quality and compliance with the durability specification

SUMMARY (cont.)

(7) *Descriptive durability requirements:*

- **It was not possible to verify and control the specified durability**
- **Higher scatter and variability of achieved construction quality were typically observed**

SUMMARY(cont.)

(8) ***Descriptive durability requirements:***

- **It was very difficult to argue about weaknesses and deficiences which occurred during concrete construction as long as the requirement to in-situ compressive strength was still fulfilled**

SUMMARY (cont.)

(9) *Documentation of achieved construction quality:*

- The required documentation of achieved construction quality distinctly clarified the responsibility of the contractor for the quality of the construction process

SUMMARY (cont.)

(10) ***Documentation of achieved construction quality:***

- The required documentation of achieved construction quality distinctly improved the workmanship giving reduced scatter and variability of achieved construction quality

SUMMARY (cont.)

(11) *Documentation of achieved construction quality:*

- For the owners it was very important to receive a documentation of achieved construction quality and compliance with the specified durability before the structures were formally handed over from the contractors

SUMMARY (cont.)

(12) *Service manual for preventive maintenance:*

- Upon completion of the structures, it was very important for the owners to receive a service manual for regular condition assessment and preventive maintenance of the structures

Future development of Singapore City

The above recommendations and guidelines for durability design and quality assurance (DURACON Model) have been adopted for the future development of Singapore City

Future development of Singapore City (cont.)

- CRP Program "Underwater Infrastructure and Underwater City of the Future" (2011 – 2015)
- *"To create space for the future development of Singapore City based on a large number sea spaced concrete substructures"*


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