SAFEGUARDING VENICE LAGOON AGAINST HIGH TIDES

OVERALL PICTURE OF THE MOSE PROJECT

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Lecture Outline

- **Introductory remarks**
  - Protection from high tides
    - Historical background
    - Selected solution
- Lagoon subsoil
- Foundation problems
- Closing remarks


Canal Grande

Palazzo Ducale

Piazza S. Marco

G-137

TAI-66

PIAZZA SAN MARCO
DURING HIGH TIDE

ISLAND OF MURANO DURING HIGH TIDE


VENICE:
A COMMERCIAL STREET
DURING HIGH TIDE

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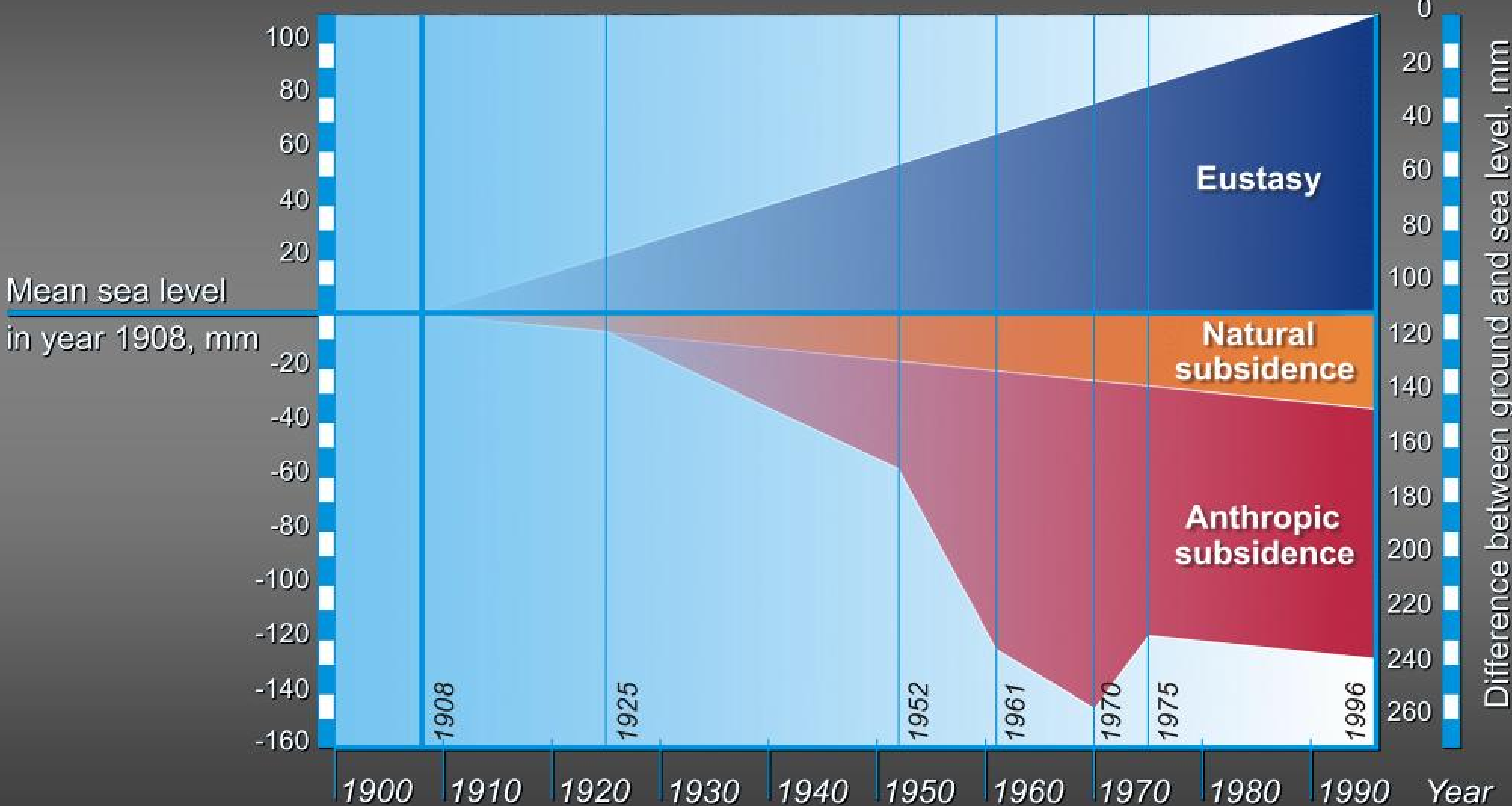
EUSTASY AND SUBSIDENCE OF VENICE FROM 1908



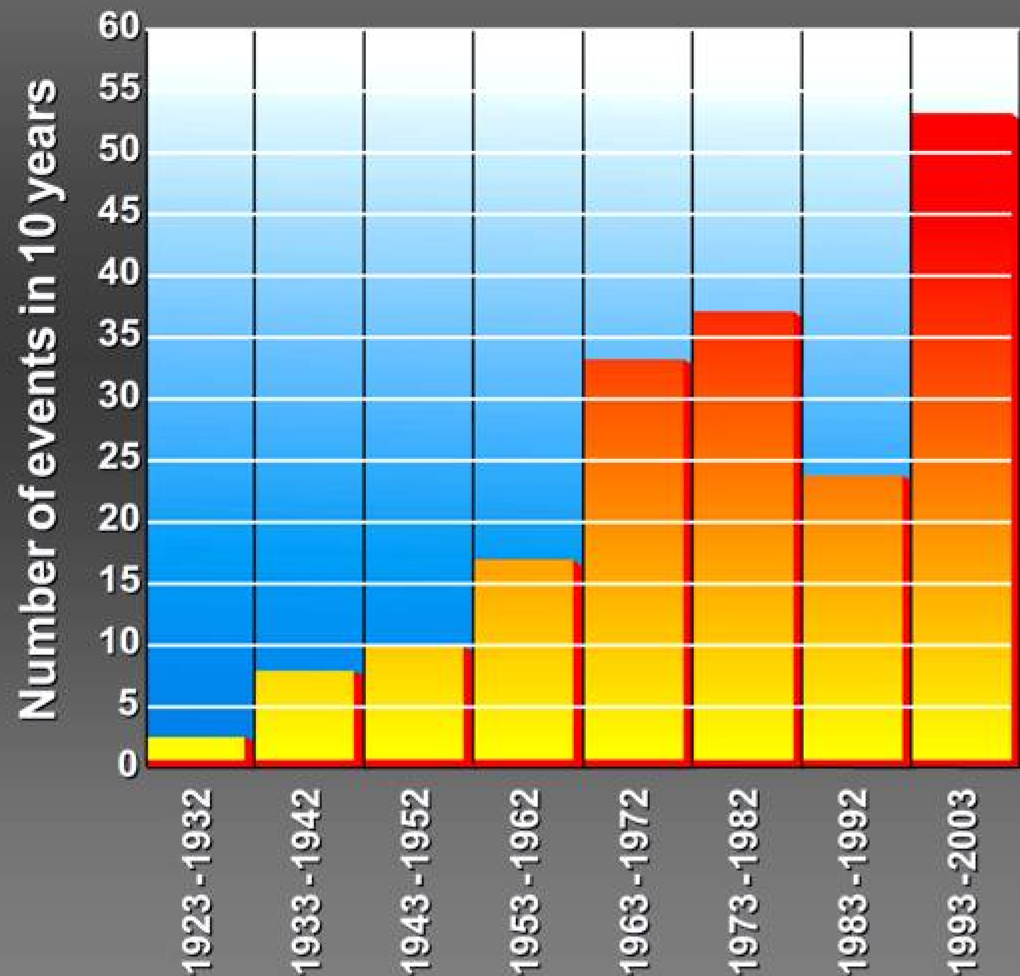
MOST IMPORTANT HIGH TIDE EVENTS SINCE 1920's

Highest tides recorded

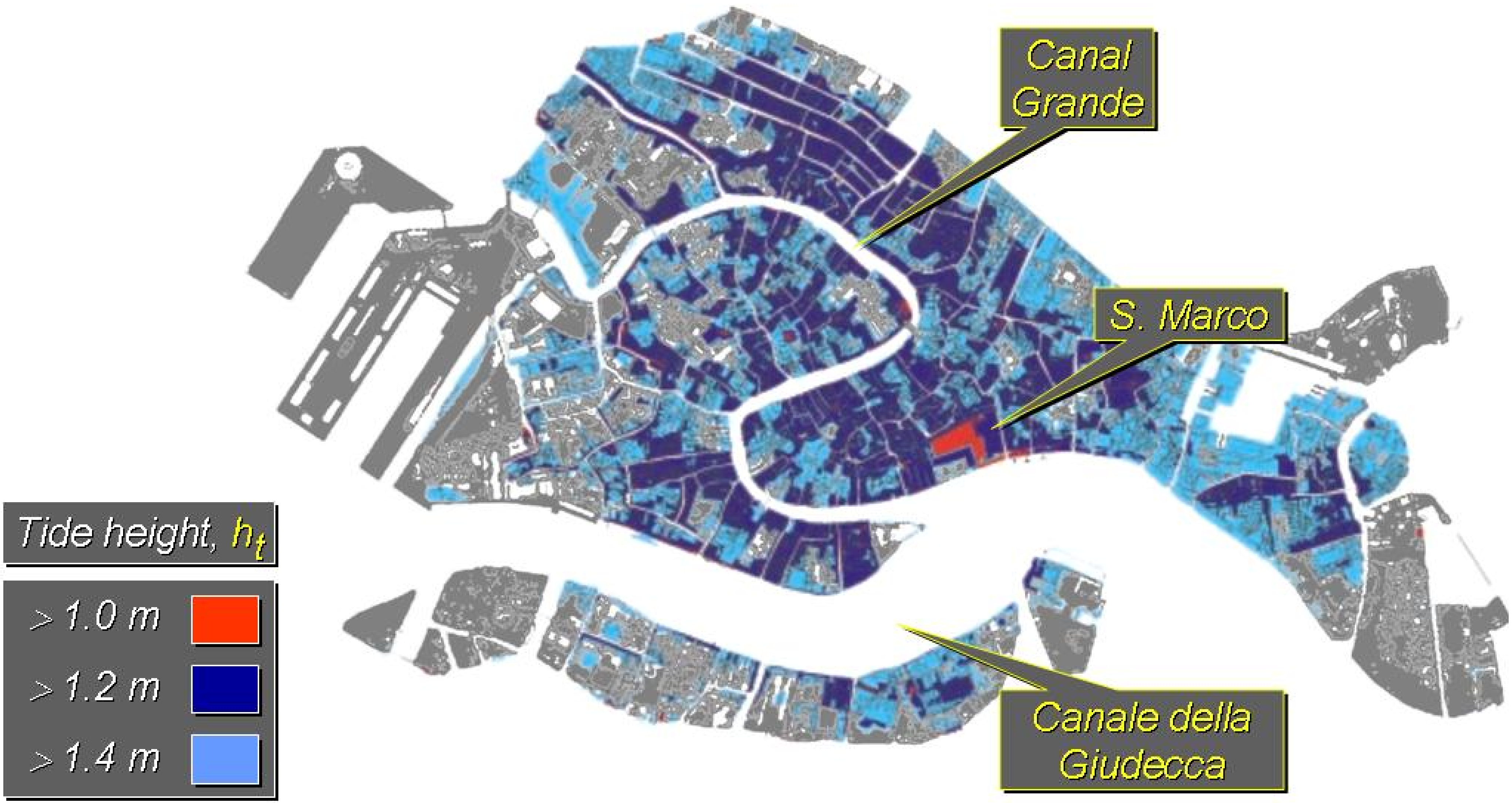
January	2003	1.10
November	2002	1.47
November	2000	1.44
Dicember	1992	1.42
February	1986	1.59
December	1979	1.66
February	1979	1.40
November	1968	1.44
November	1966	1.94
October	1960	1.45
November	1951	1.51

Highest tides recorded, *meters*

High water events frequency



VENICE: AREAS FLOODED DURING HIGH TIDES



SAFEGUARDING THE VENICE LAGOON AGAINST HIGH TIDES

ANTIFLOOD BARRIERS AT THREE INLETS

1. Mobile barrier
2. Breakwater
3. Refuge haven
4. Navigation lock

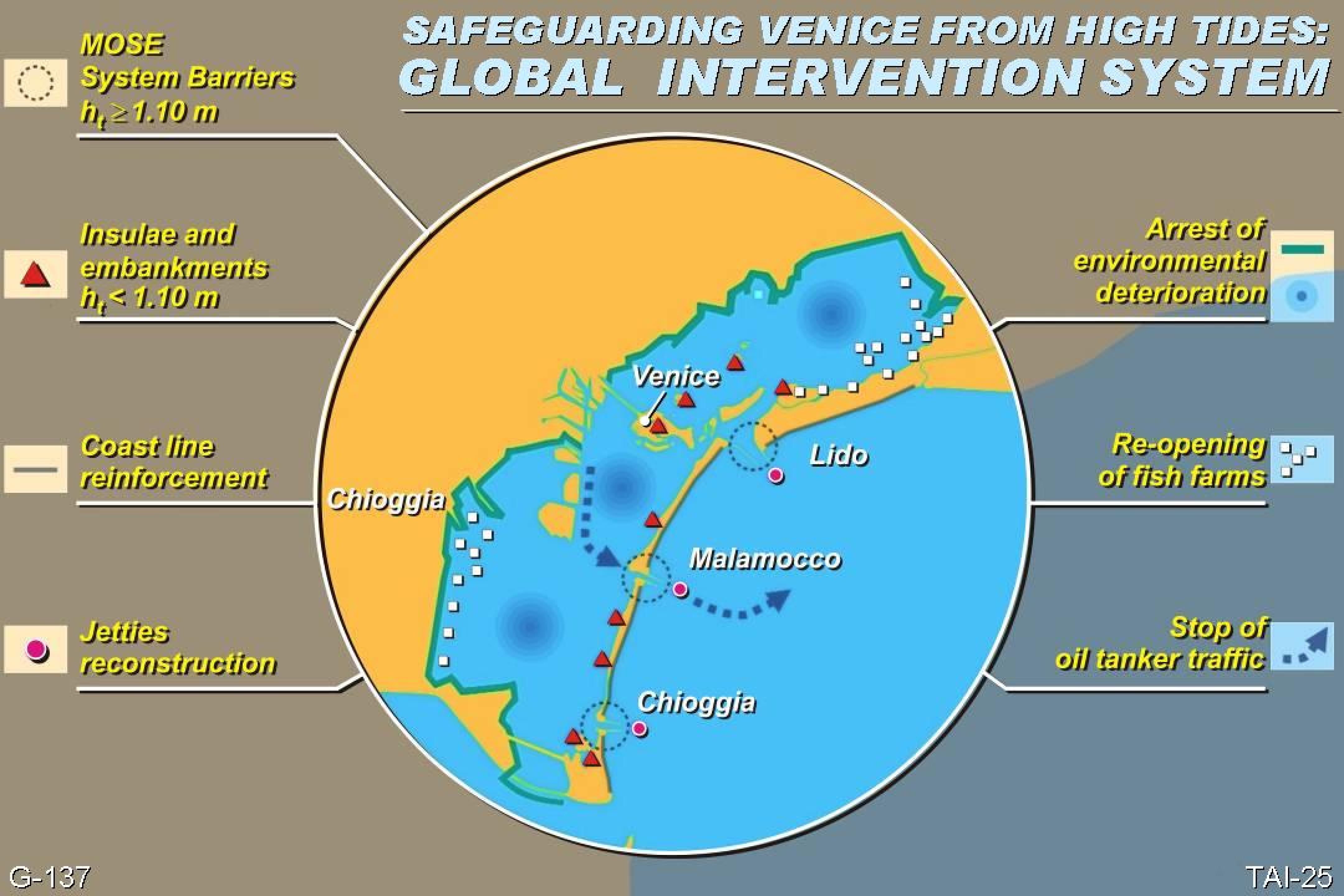
LIDO INLETS

MALAMOCCO INLET

CHIOGGIA INLET

TAI-15

G-137


SAFEGUARDING VENICE FROM HIGH TIDES:
GLOBAL INTERVENTION SYSTEM
MOSE
System Barriers
$h_t \geq 1.10$ m
Insulae and
embankments
$h_t < 1.10$ m
Coast line
reinforcement
Jetties
reconstruction
Arrest of
environmental
deterioration
Re-opening
of fish farms
Stop of
oil tanker traffic
Venice
Lido
Chioggia
Malamocco
Chioggia
G-137
TAI-25

Lecture Outline

- Introductory remarks
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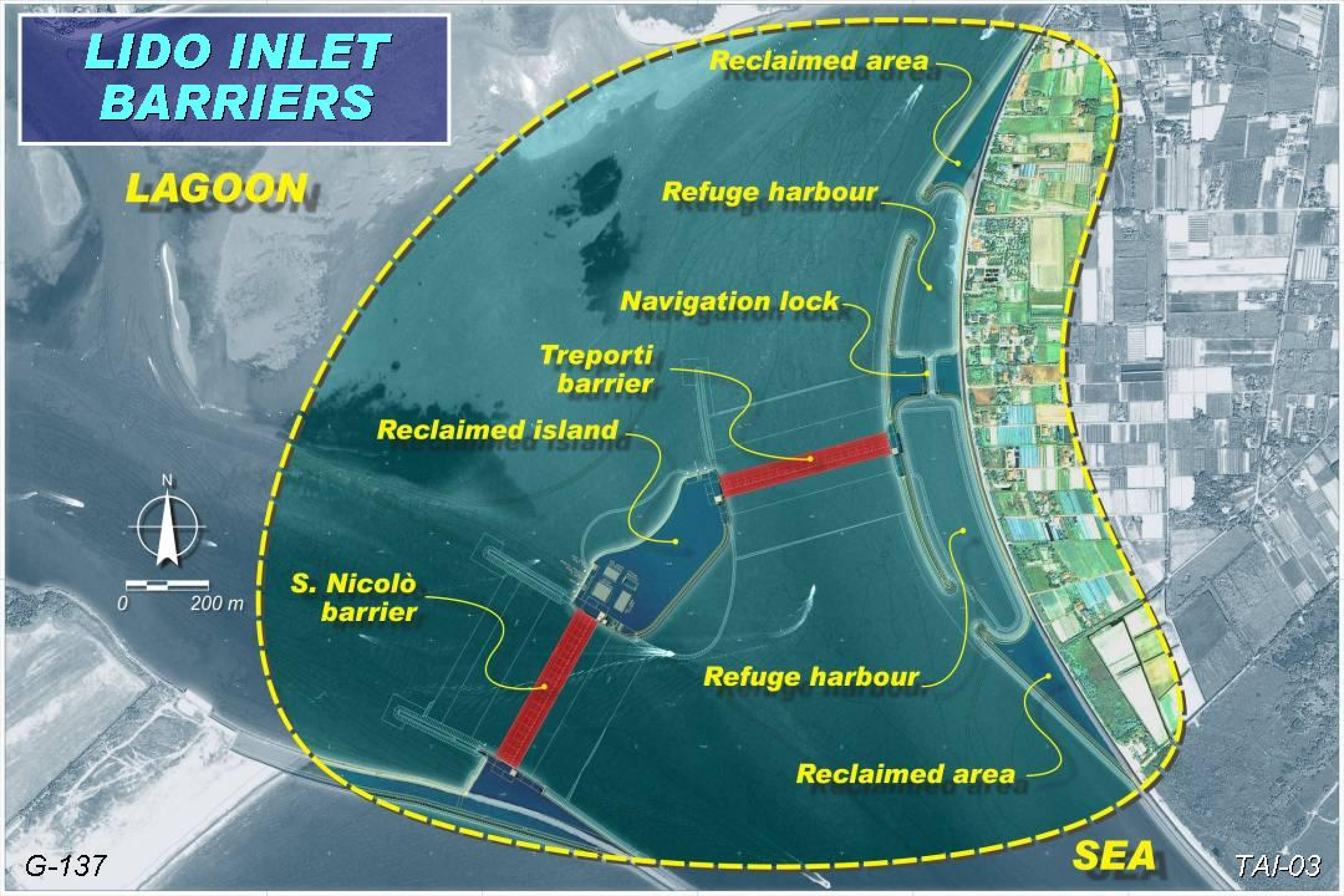
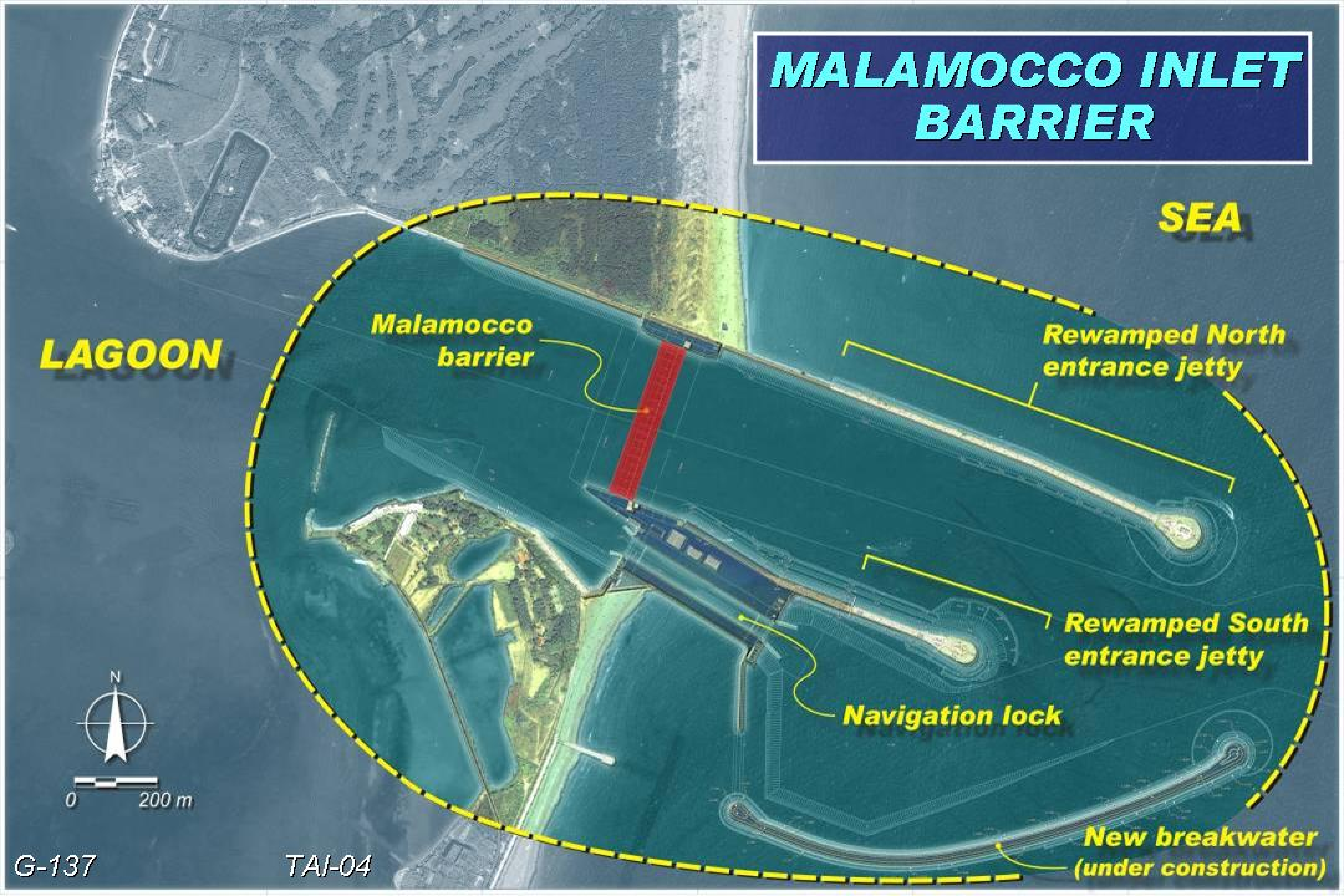
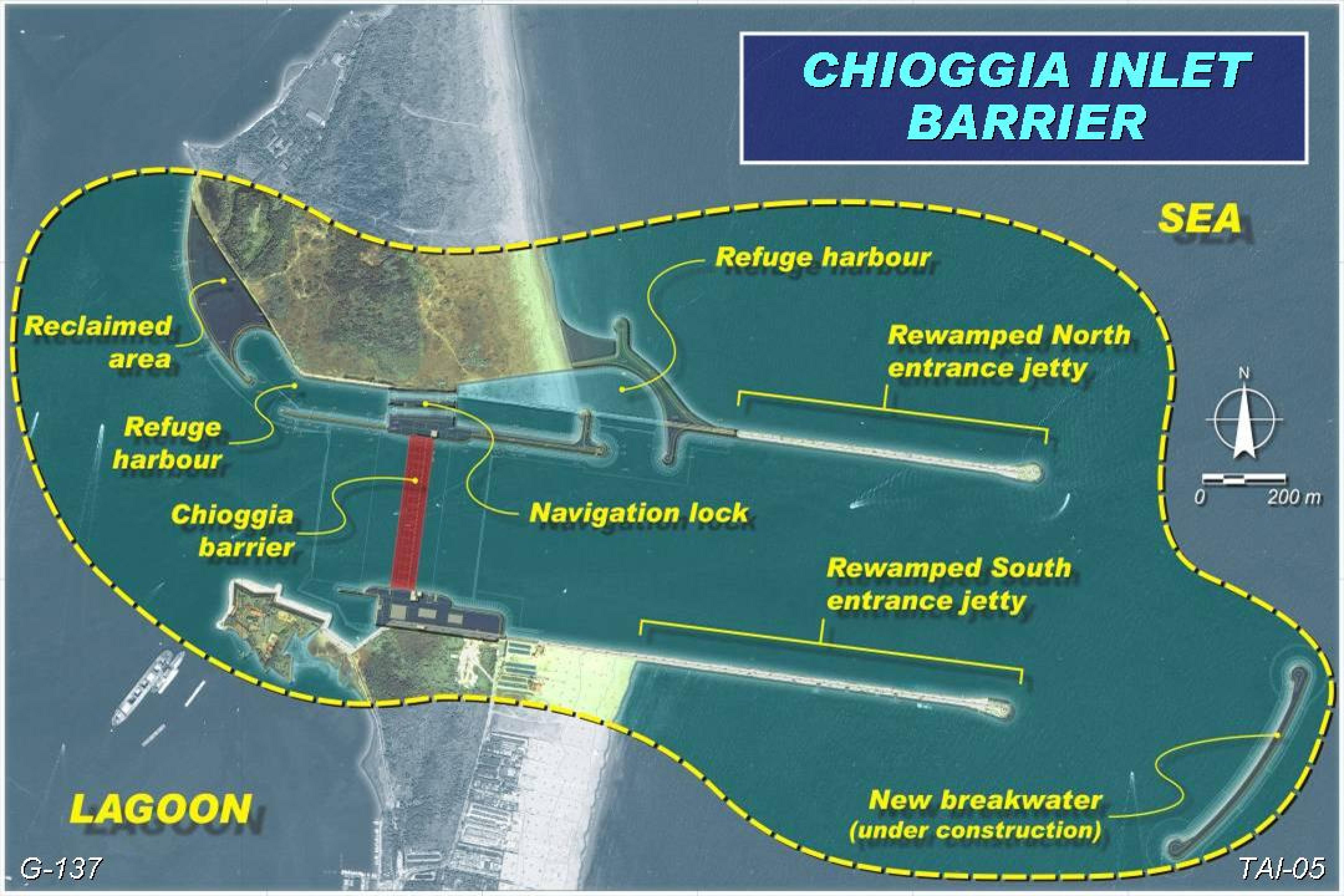

LIDO INLET BARRIERS
LAGOON
Reclaimed area
Refuge harbour
Navigation lock
Treporti barrier
Reclaimed island
S. Nicolò barrier
Refuge harbour
Reclaimed area
SEA
N
0
200 m
G-137
TAI-03



MALAMOCCO INLET BARRIER
SEA
LAGOON
Malamocco barrier
Rewamped North entrance jetty
Rewamped South entrance jetty
Navigation lock
New breakwater (under construction)
N
0
200 m
G-137
TAI-04


CHIOGGIA INLET BARRIER
SEA
Refuge harbour
Reclaimed area
Rewamped North entrance jetty
N
0
200 m
Refuge harbour
Chioggia barrier
Navigation lock
Rewamped South entrance jetty
New breakwater (under construction)
LAGOON
G-137
TAI-05

MALAMOCCO BARRIER: STANDARD CAISSON EMBODYING THE GATE

1. Caisson
2. Flood gate
3. Ballast (water)
4. Ballast (concrete)
5. Plant and access tunnels
6. Sheet pile
7. Settlement reducing piles

THE MOSE SYSTEM: GENERAL FEATURES

MOBILE OSCILLATING BOUNCY FOLD AWAY FLAP GATES :

Lido - Treporti	inlet:	21 gates
Lido - San Nicolò	inlet:	20 gates
Malamocco	inlet:	19 gates
Chioggia	inlet:	18 gates

COMPLEMENTARY INTERVENTIONS:

- Breakwaters at the front of each inlet, sea-side
- Refuge havens and navigation locks
- Raise of banks and public walkways
- Morphological intervention on selected lagoon areas

SAFEGUARDING VENICE FROM FLOODS
BODIES INVOLVED

Lecture Outline

- Introductory remarks
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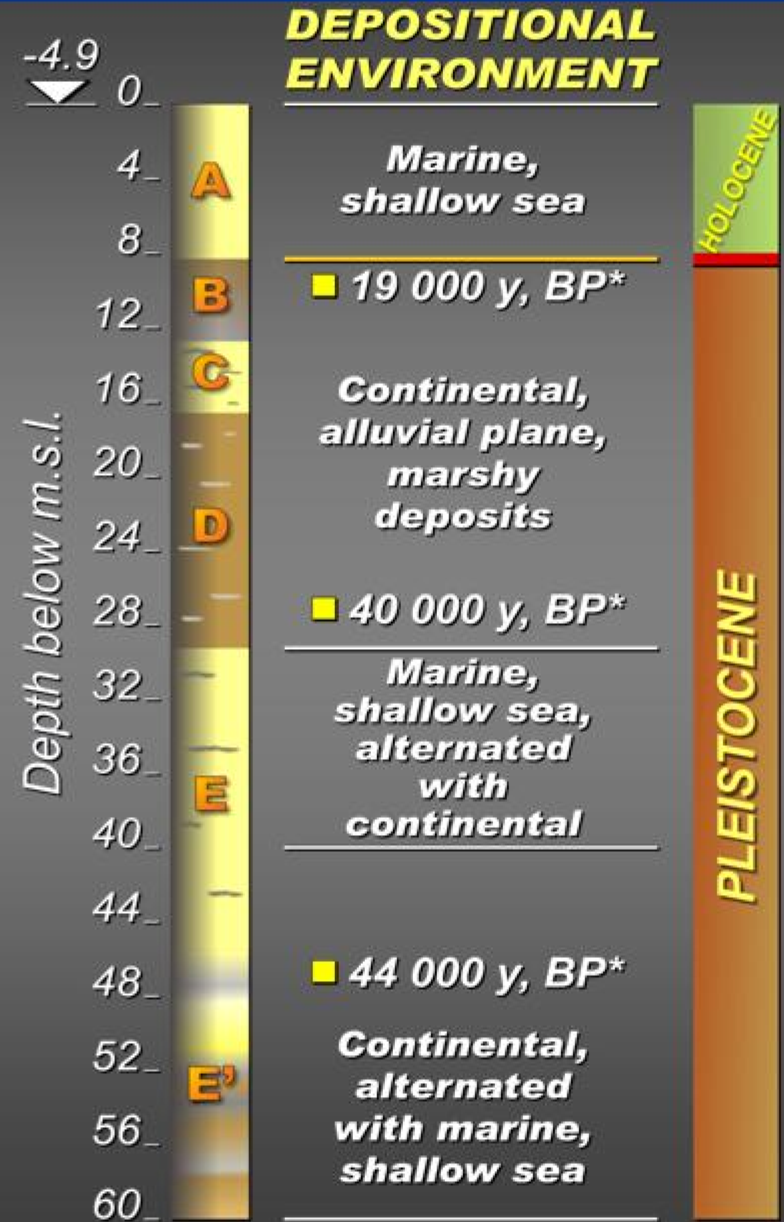
  - Historical background
  - Selected solution
- **Lagoon subsoil**
- Foundation problems
- Closing remarks

MALAMOCCO INLET - SCHEMATIC DEPOSITIONAL HISTORY

Belloni and Caielli (1997)



- **A** "Coarse grained", shallow sea deposits
- **B** "Fine grained" lacustrine and swamp deposits, covered by a layer of dessiccated silty Clay (Caranto)
- **C** "Coarse and fine grained" alluvial deposits
- **D** "Fine grained" coastal plane alluvial deposits
- **E** "Coarse grained" coastal plane alluvial deposits
- **E'** "Fine grained" coastal plane and shallow sea deposits
- "Caranto" - end of Pleistocene deposition

(*) Radio Carbon C_{14}

SITE INVESTIGATION FOR FINAL DESIGN

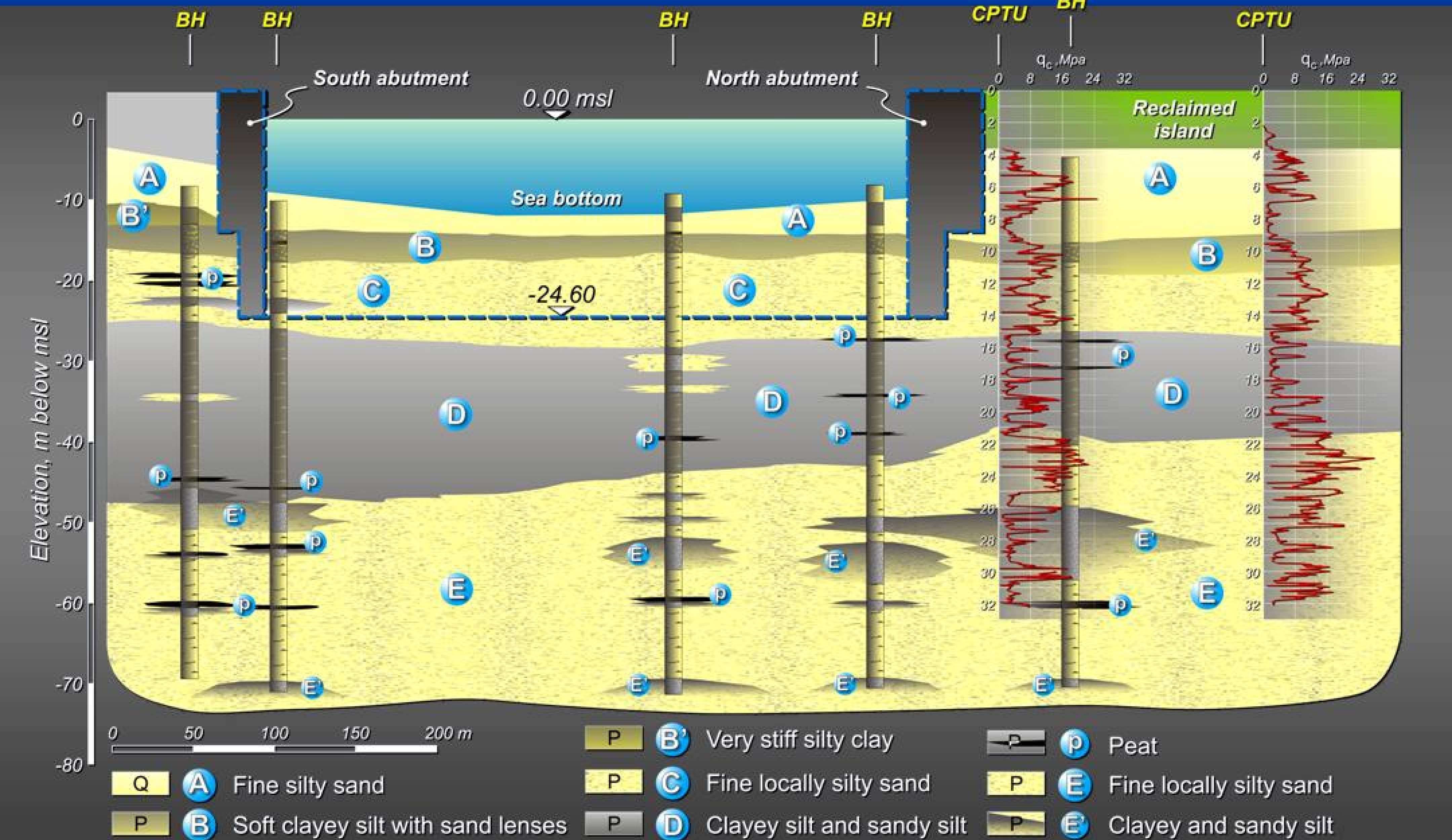
(2001 to 2004)

BH	CPTU	DMT	SPT-BH
n°88, depth 40 to 120 m	n°119, depth 30 to 120 m	n°11, depth 50 m	n°13, depth 40 to 50 m

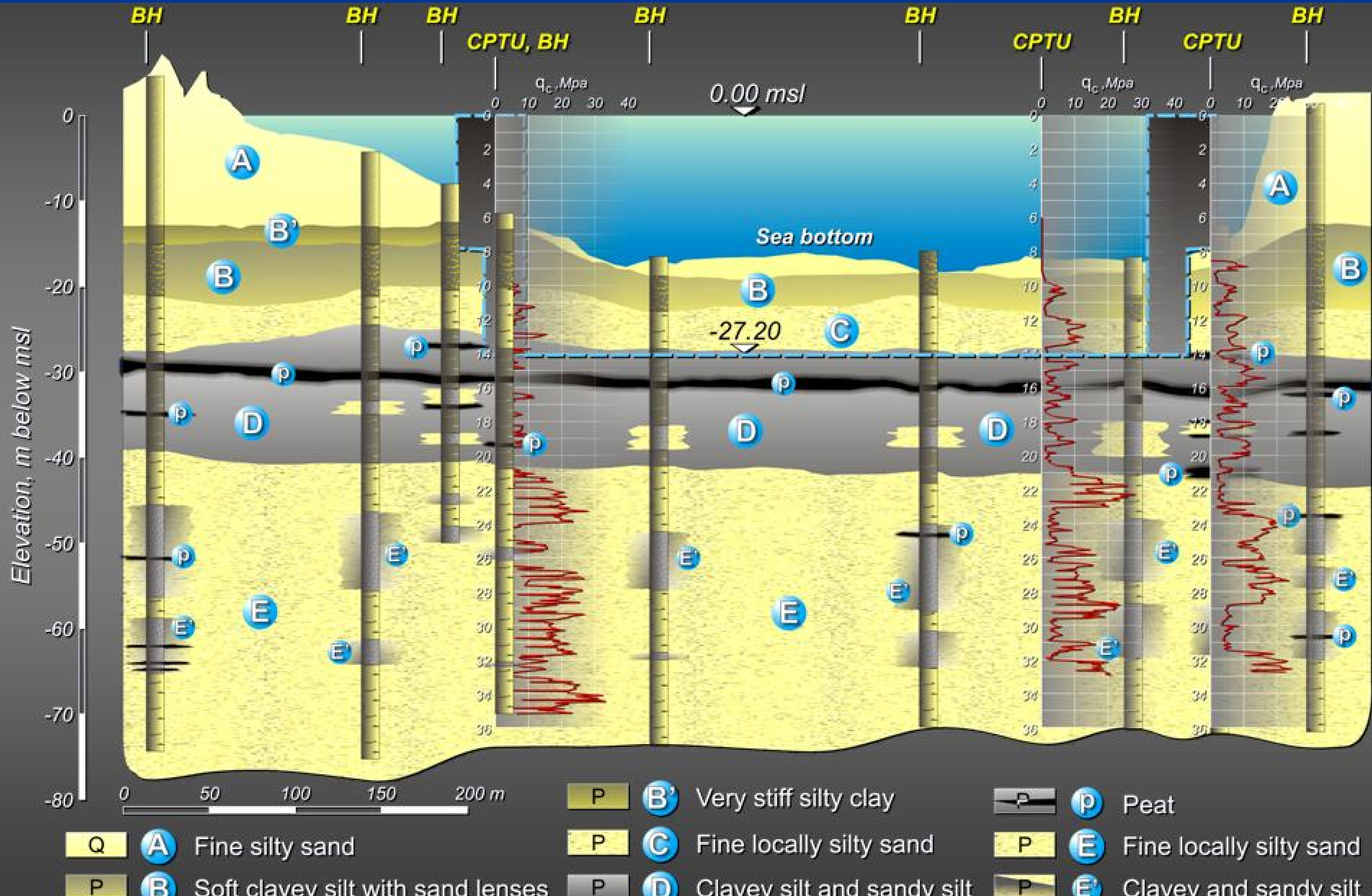
- **BH** ▶ Geotechnical borings; undisturbed sampling, **SPT's**, **FVT's**
- **CPTU** ▶ Static Cone Penetration Test with pore pressure measurement
- **DMT** ▶ Marchetti's Flat Dilatometer Test
- **SPT-BH** ▶ Standard Penetration Test, carried out in dedicated 3" O.D. holes

- Undisturbed samples retrieved by means of Osterberg Piston Sampler 98 mm O.D.
- 3 CH tests carried out, each employing three 80 deep-holes
- Rod energy measured in one of SPT-BH, ER = 63 %

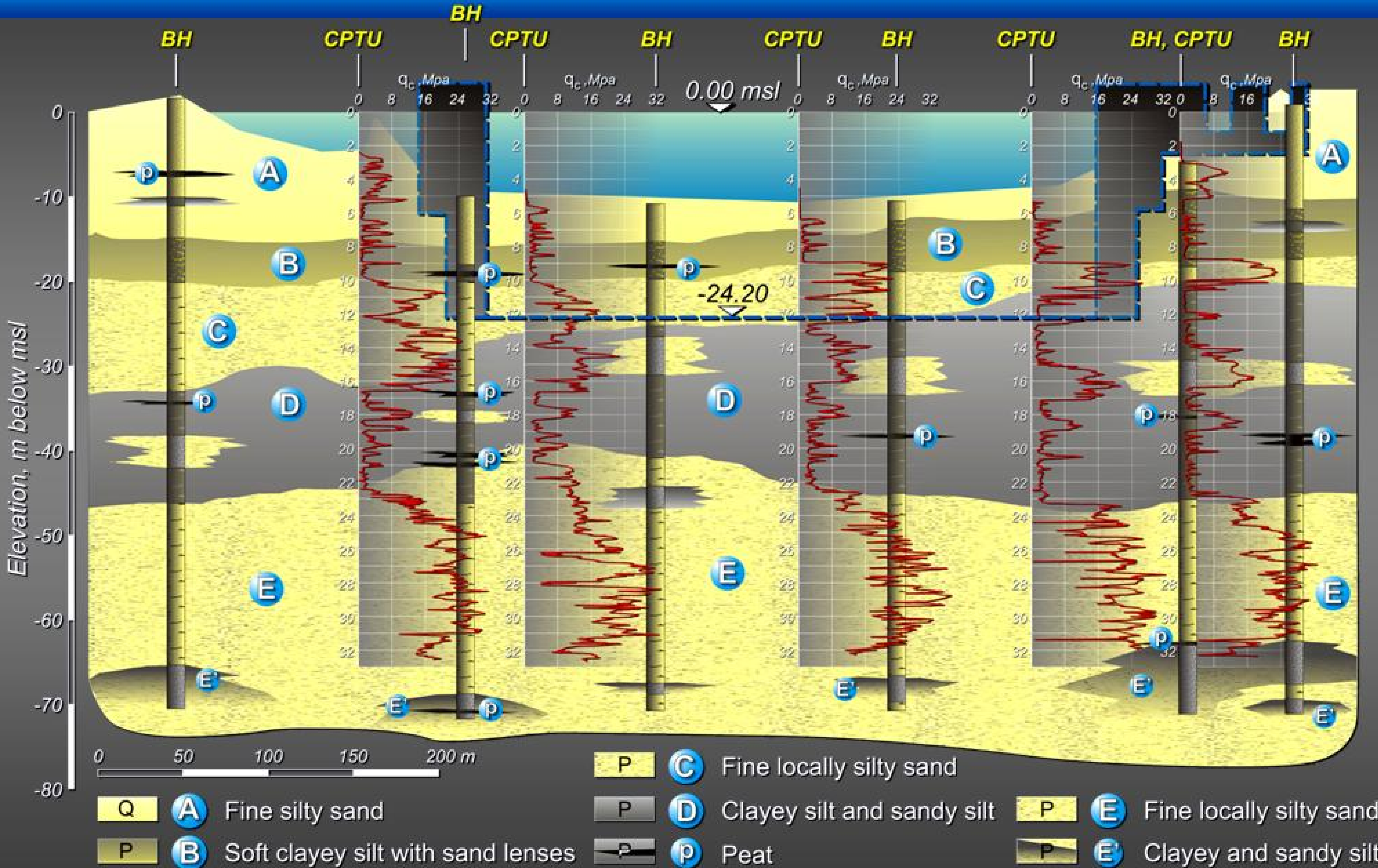
LIDO INLET – SAN NICOLO' BARRIER – SUBSOIL CONDITIONS



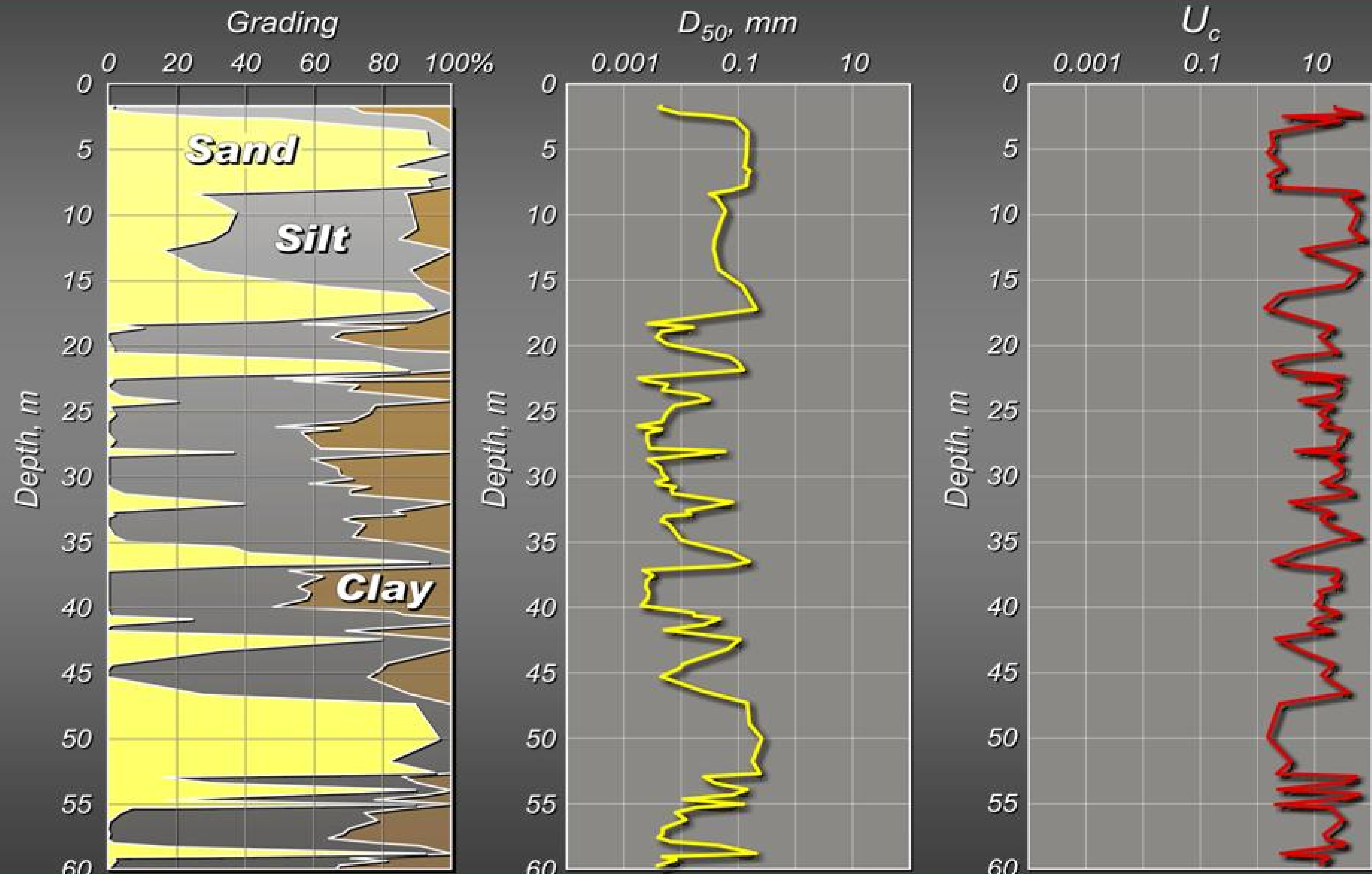
MALAMOCCO BARRIER – SUBSOIL CONDITIONS



CHIOGGIA INLET BARRIER – SUBSOIL CONDITIONS



LIDO TRIAL EMBANKMENT
SOIL GRADING VARIATION WITH DEPTH

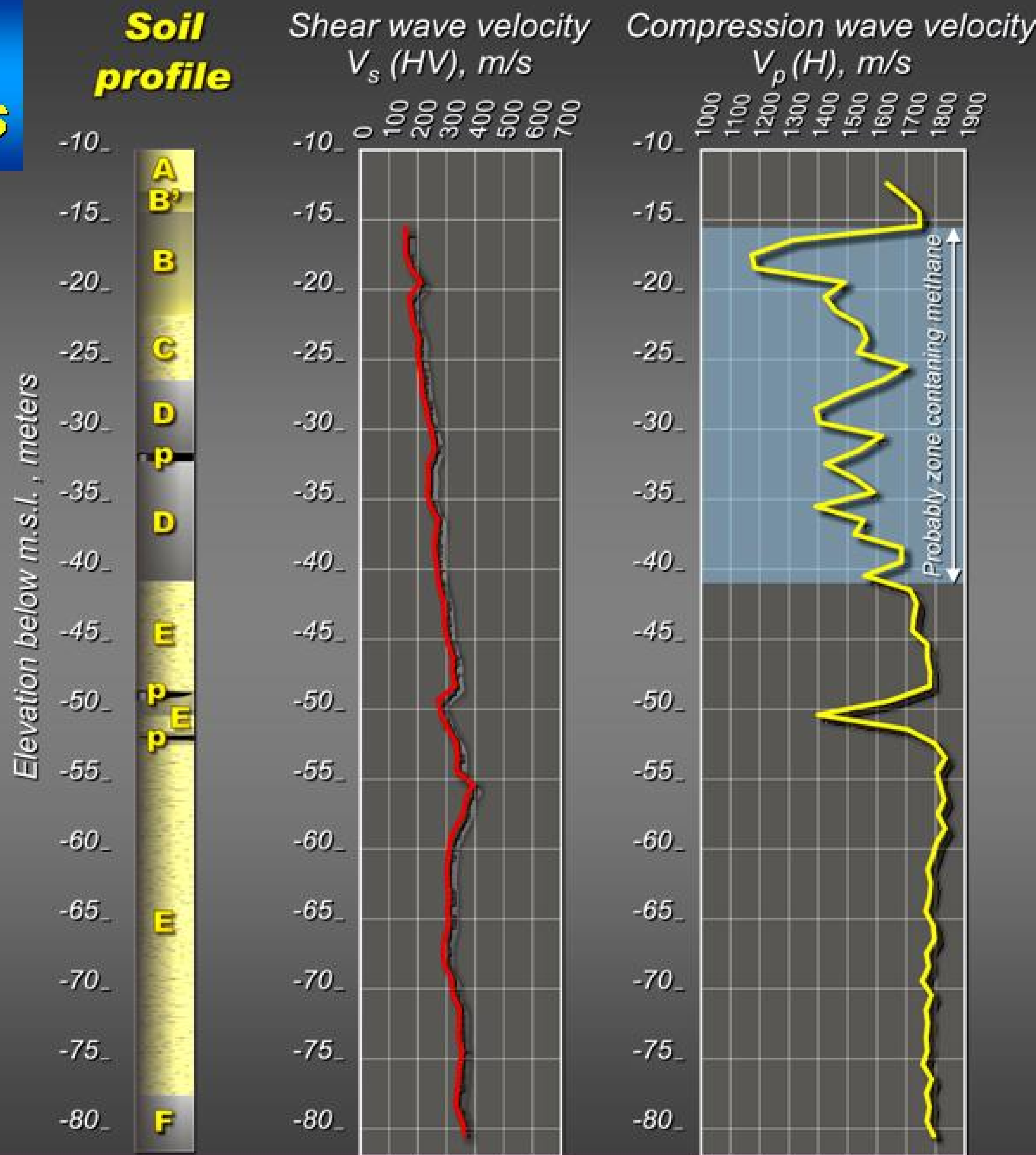


Ricceri et al. (2004)

LAGOON DEPOSITS
EXAMPLES OF HETEROGENEITY AT SMALL SCALE

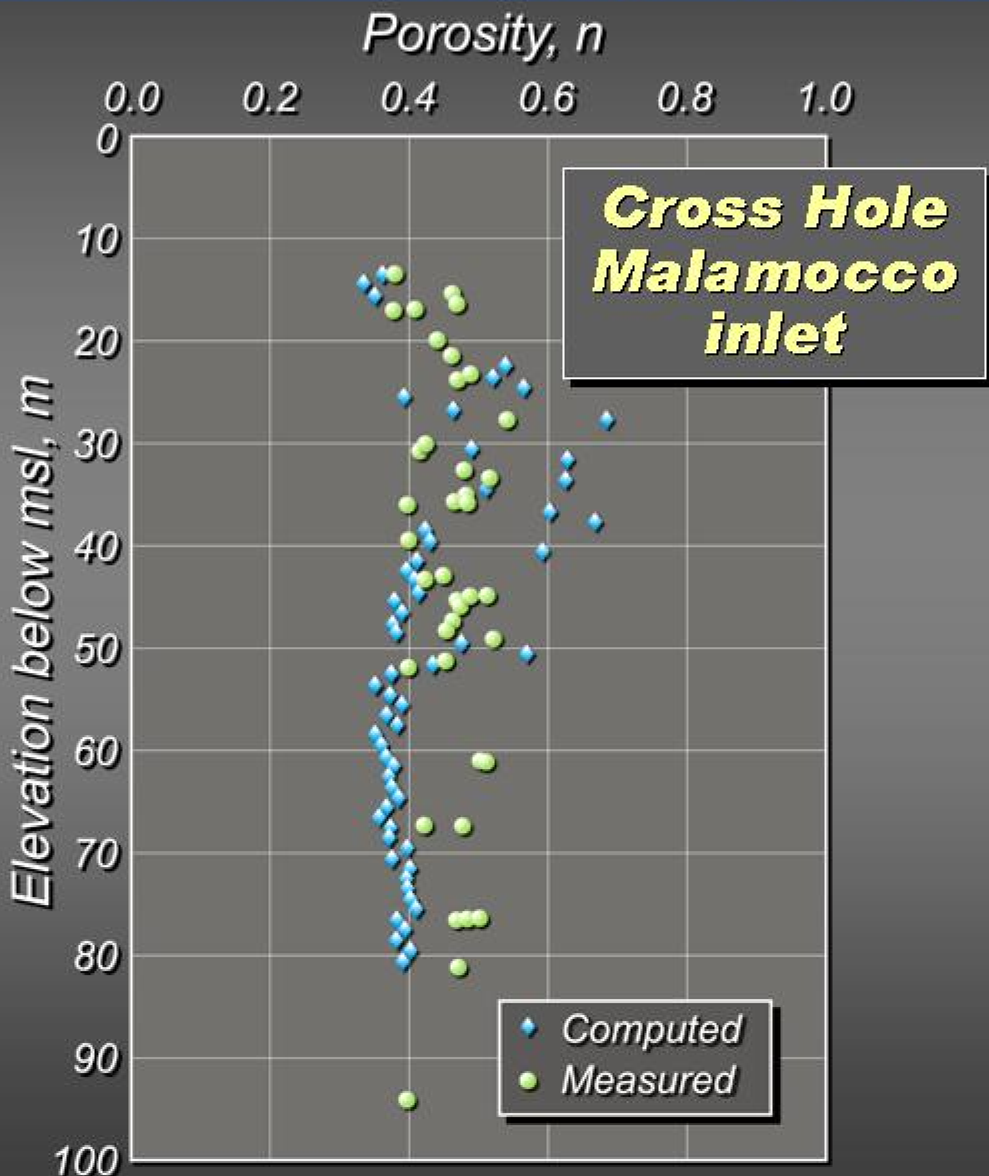
PRONOUNCED VARIABILITY OF INDEX AND MECHANICAL SOIL PROPERTIES IN BOTH VERTICAL AND HORIZONTAL DIRECTION

MALAMOCCO INLET
CROSS-HOLE TEST RESULTS



- **A** Fine silty sand
- **B** Soft clayey silt with sand lenses
- **B'** Very stiff silty clay
- **C** Fine locally silty sand
- **D** Clayey silt and sandy silt
- **p** Peat
- **E** Fine locally silty sand
- **E'** Clayey and sandy silt
- **F** Clayey silt and sandy silt

MALAMOCCO INLET
POROSITY FROM SEISMIC AND LABORATORY TESTS



Lancellotta (2001), Foti et al. (2002)

$$n = \frac{\rho_s - \left[\rho_s^2 - \dfrac{4(\rho_s - \rho_f)K_f}{V_p^2 - 2\left(\dfrac{1-\nu_s}{1-2\nu_s}\right)V_s^2} \right]^{0.5}}{2(\rho_s - \rho_f)}$$

Connected porosity

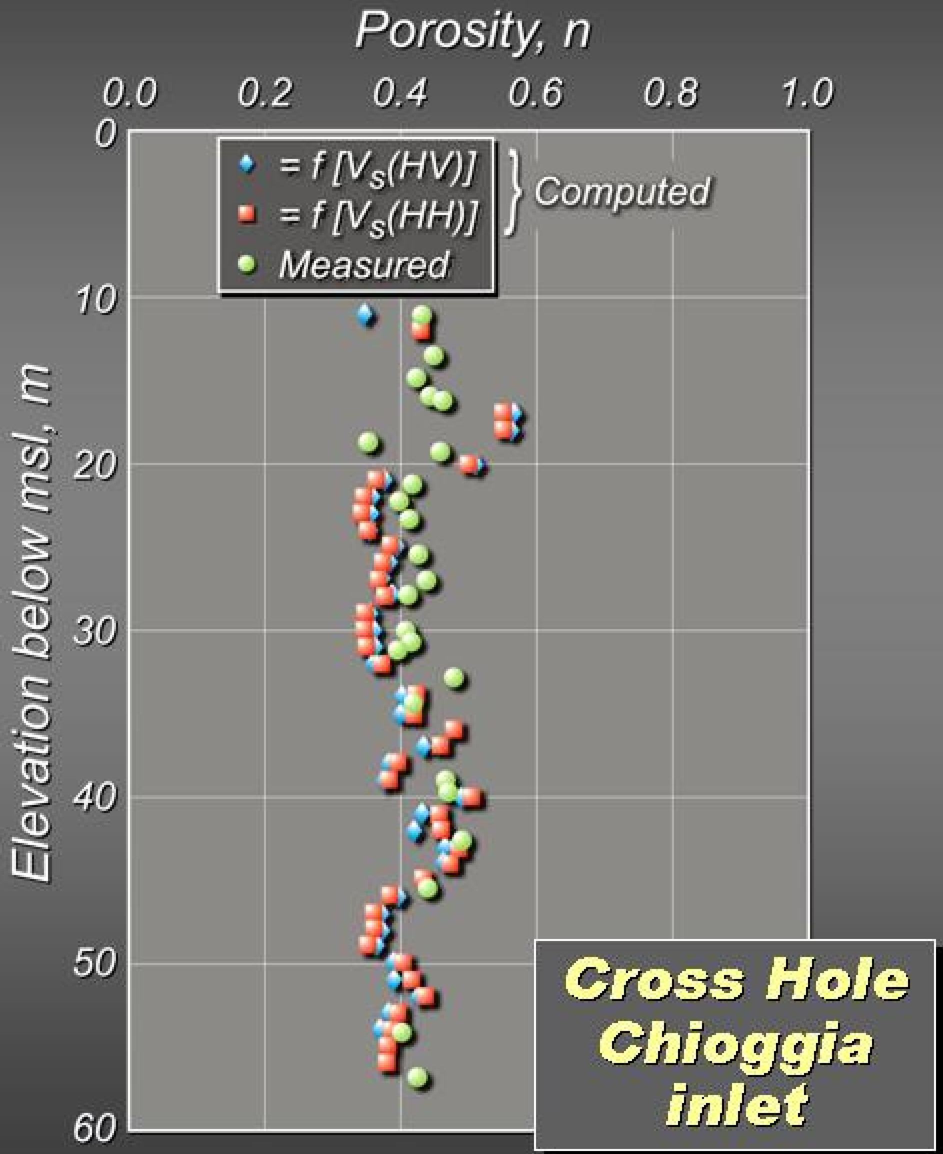
ρ_s = soil particles } mass

ρ_f = pore fluid } density

K_f = bulk modulus of pore fluid

ν_s = Poisson ratio of soil skeleton

CHIOGGIA INLET
POROSITY FROM SEISMIC AND LABORATORY TESTS



Lancellotta (2001), Foti et al. (2002)

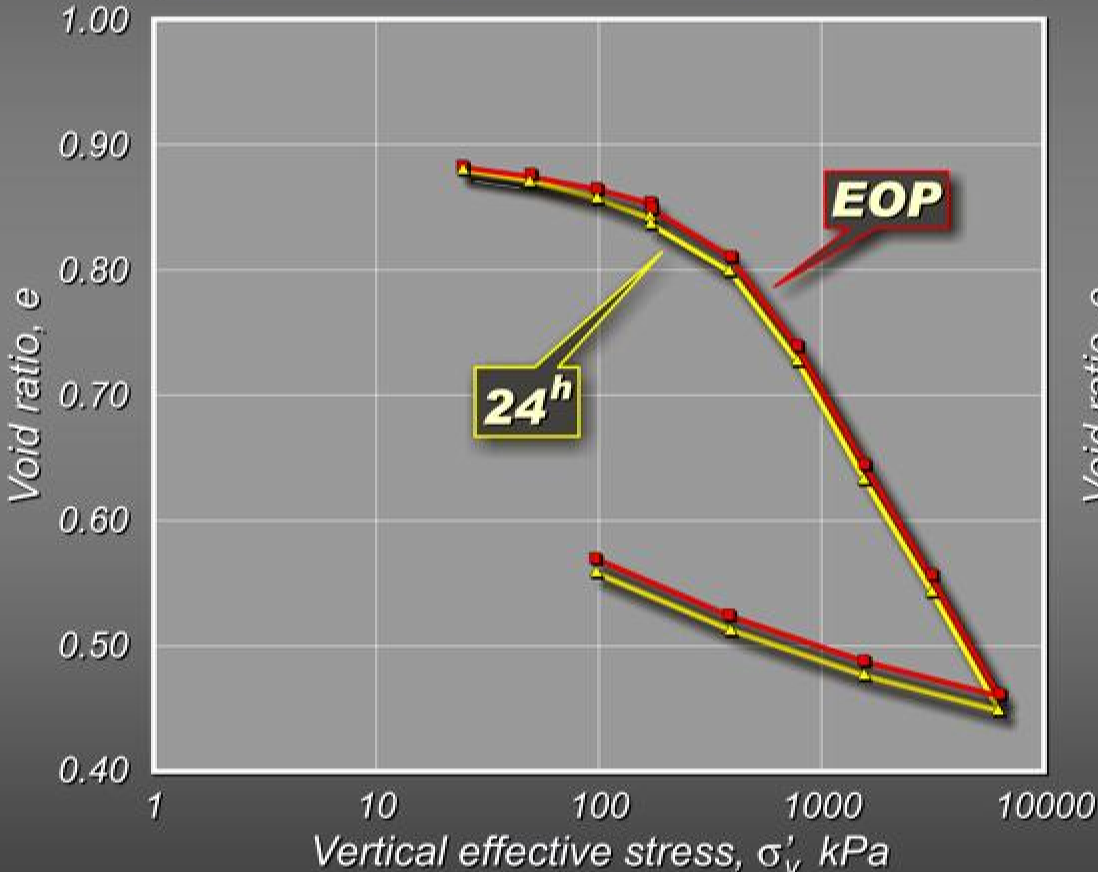
$$n = \frac{\rho_s - \left[\rho_s^2 - \dfrac{4(\rho_s - \rho_f)K_f}{V_p^2 - 2\left(\dfrac{1-\nu_s}{1-2\nu_s}\right)V_s^2}\right]^{0.5}}{2(\rho_s - \rho_f)}$$

Connected porosity

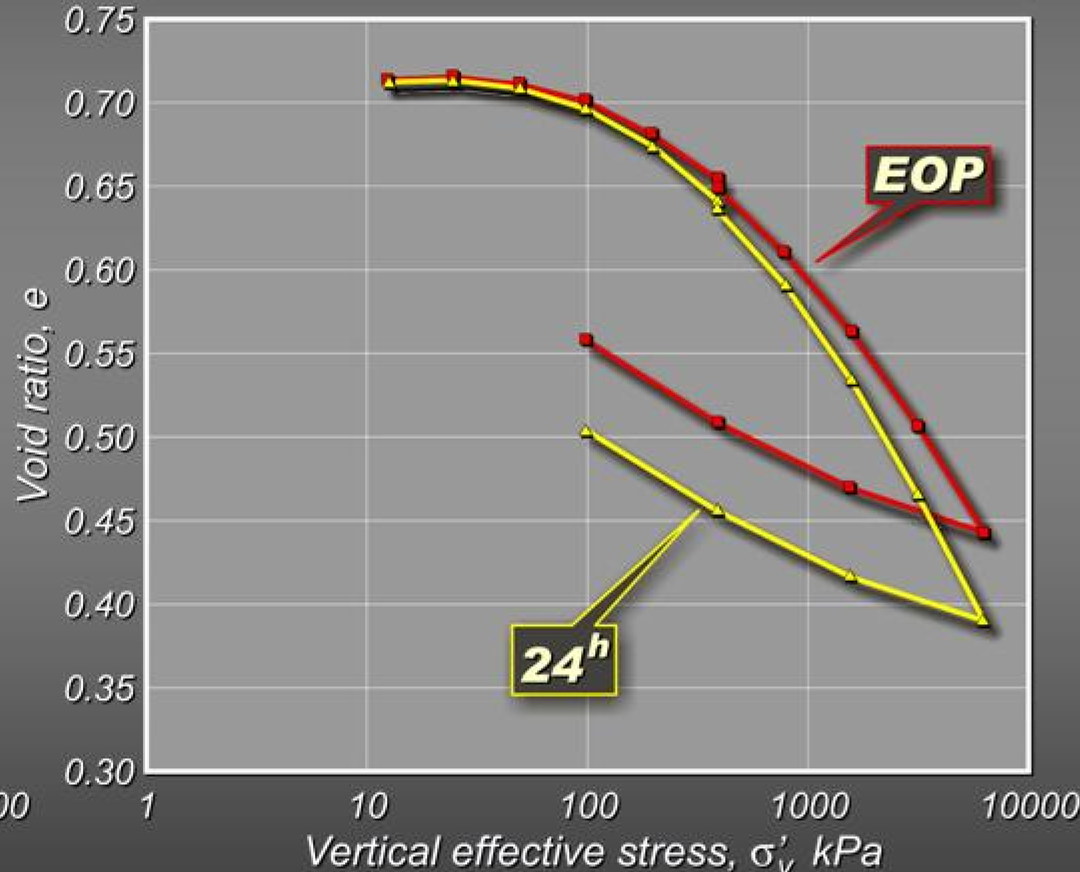
ρ_s	=	soil particles	mass density
ρ_f	=	pore fluid	
K_f	=	bulk modulus of pore fluid	
ν_s	=	Poisson ratio of soil skeleton	

LIDO INLET – EXAMPLES OF OEDOMETER TESTS

Depth 20.2 m*
Clayey Silt, $e_0 = 0.885$, $\gamma_n = 18.93$ kN/m^3
Sand: 3%, Silt: 62%, Clay: 35%
$W_n = 34.8\%$; $LL = 42.0\%$; $PI = 23.0\%$



Depth 43.8 m*
Silty Clay, $e_0 = 0.715$, $\gamma_n = 19.66$ kN/m^3
Sand: 5%, Silt: 48%, Clay: 47%
$W_n = 27.3\%$; $LL = 50.0\%$; $PI = 23.1\%$



(*) Depth below sea bottom at -10.0 m below m.s.l.

VENETIAN LAGOON: LOCATION OF TRIAL EMBANKMENT

Treporti
Experimental Site:
Trial Embankment

TRIAL EMBANKMENT

During construction

Reinforced earth wall

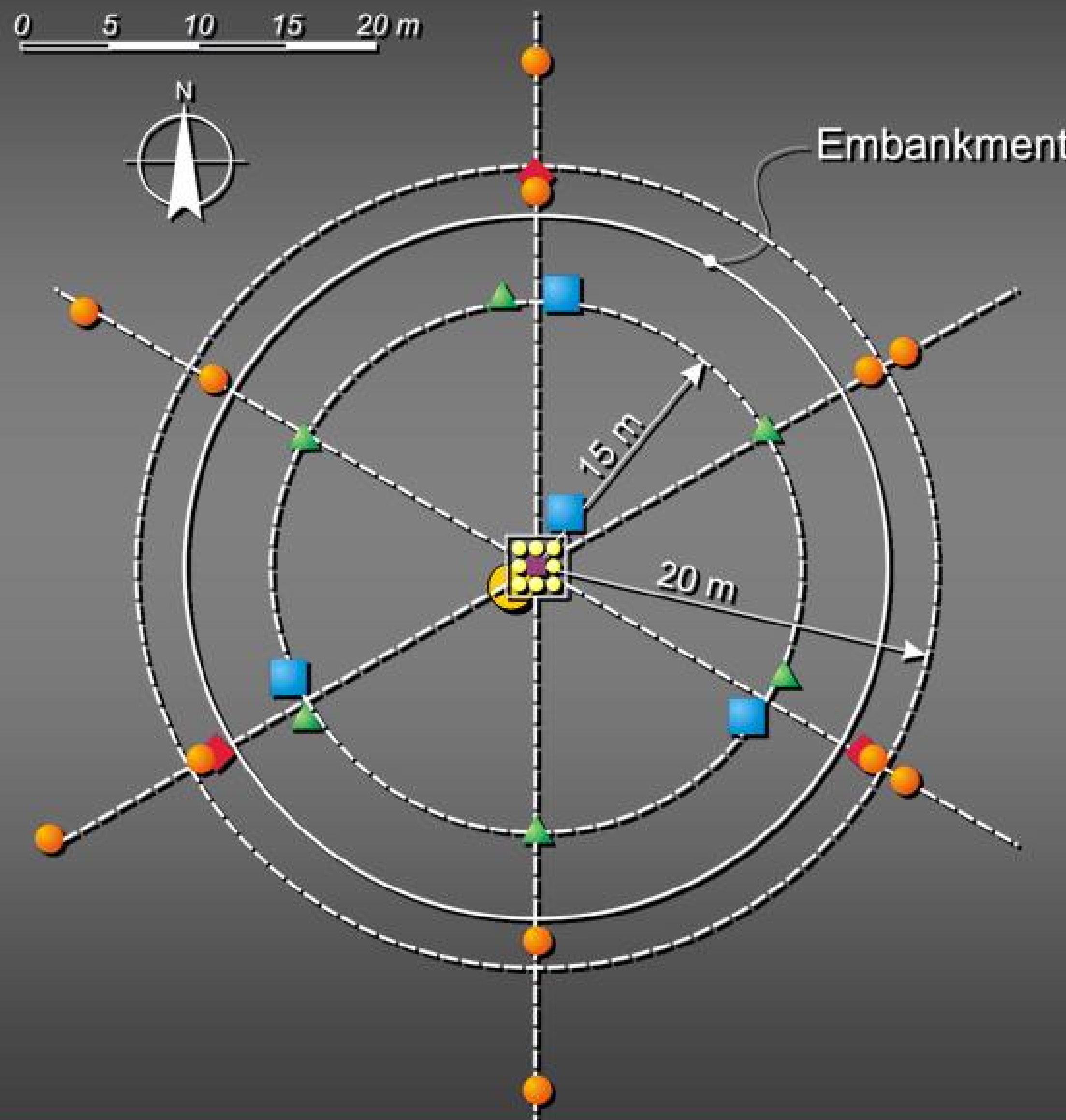
Completed

TRIAL EMBANKMENT: MONITORING INSTRUMENTATION

Ricceri et al. (2004)

Instruments location

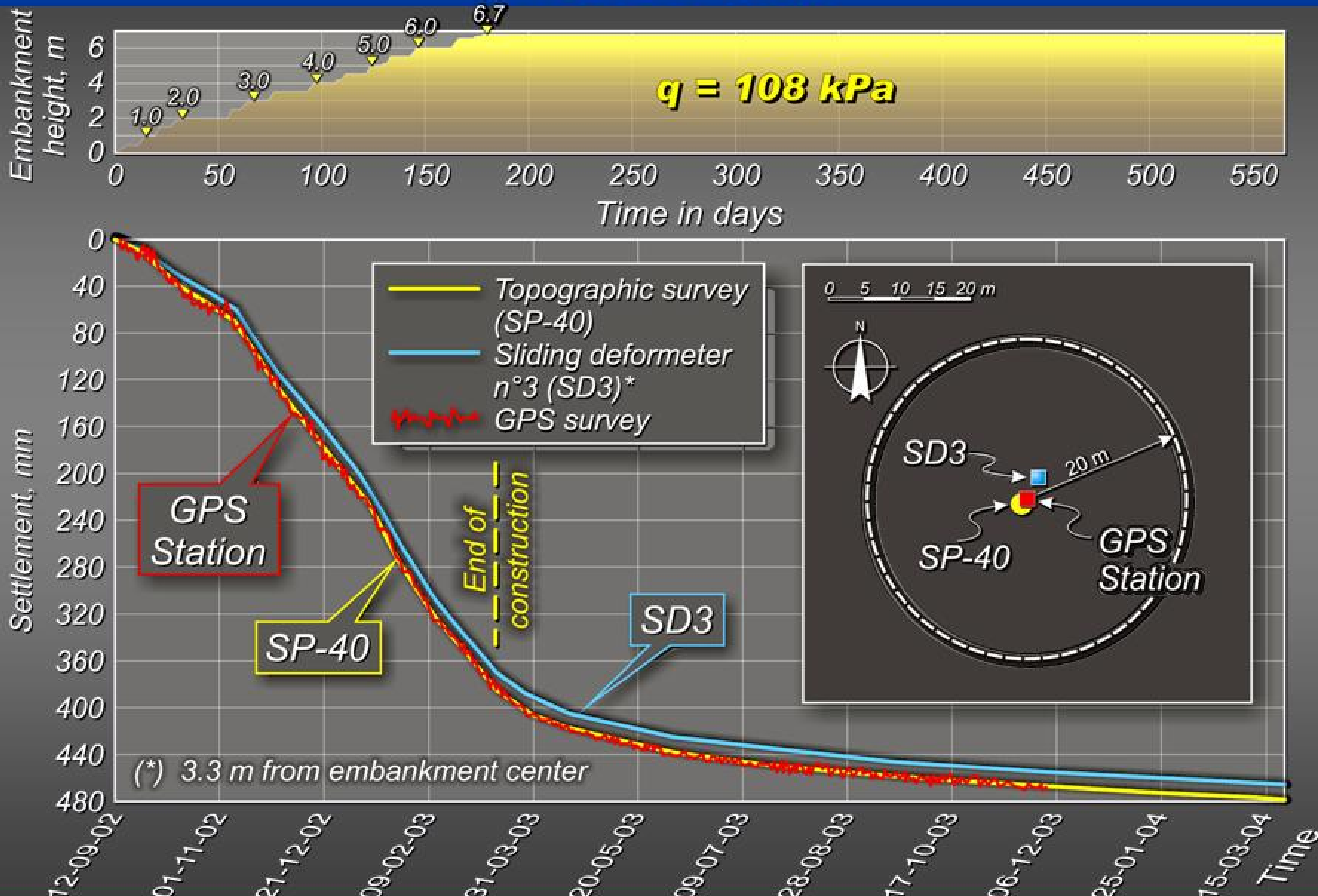
- GPS station
- Deep settlement plates
- Sliding deformeters
- Inclinometers
- Benchmarks
- Surface settlement plates
- Topographic survey



NOTE:
Have been also installed:
15 vibrating wire piezometers
20 Casagrande's piezometers
5 total stress cells

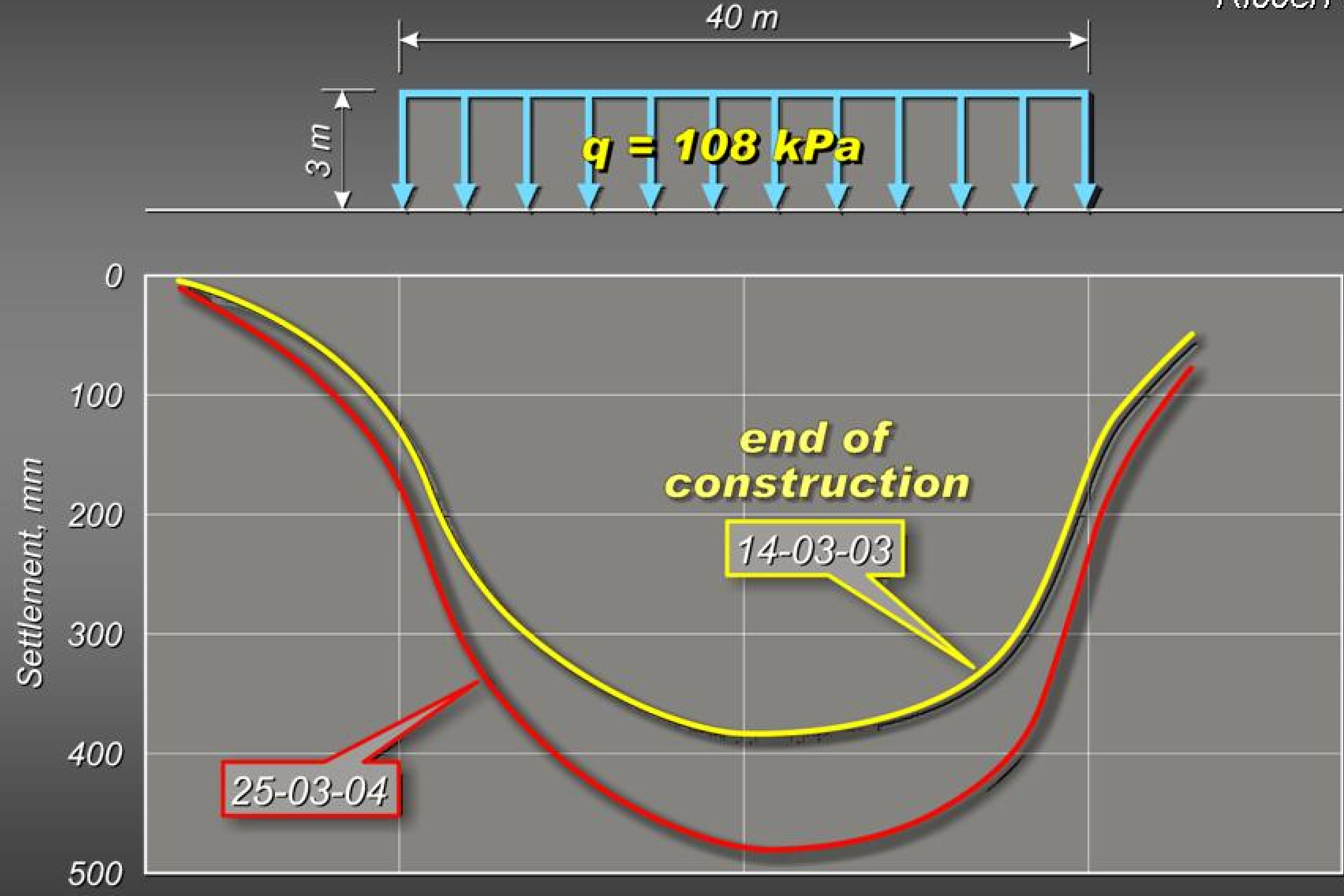
CENTER OF TRIAL EMBANKMENT: TIME-SETTLEMENT CURVE

Ricceri et al. (2004)

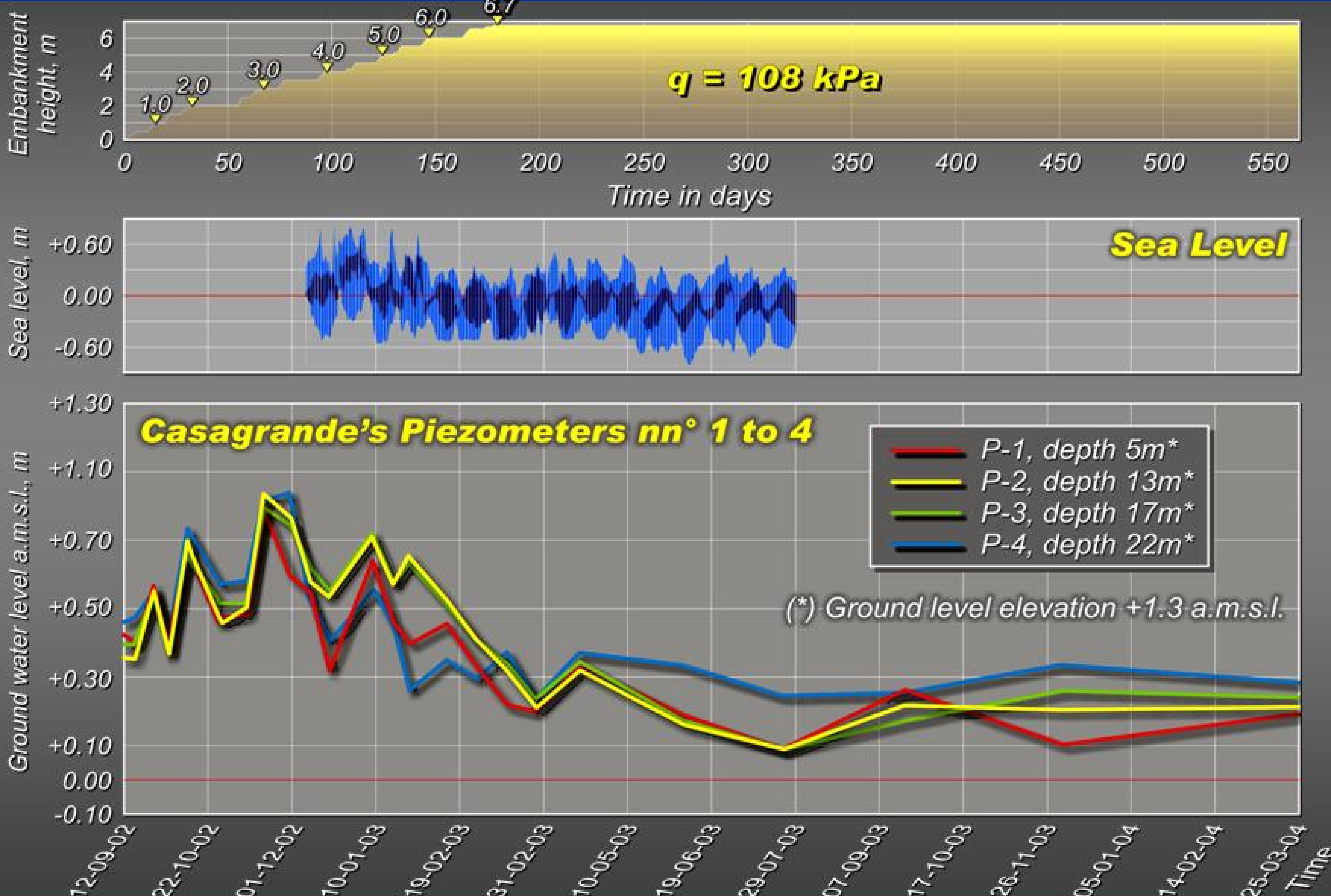


LIDO INLET - TRIAL EMBANKMENT
GROUND SURFACE SETTLEMENT

Ricceri et al. (2004)



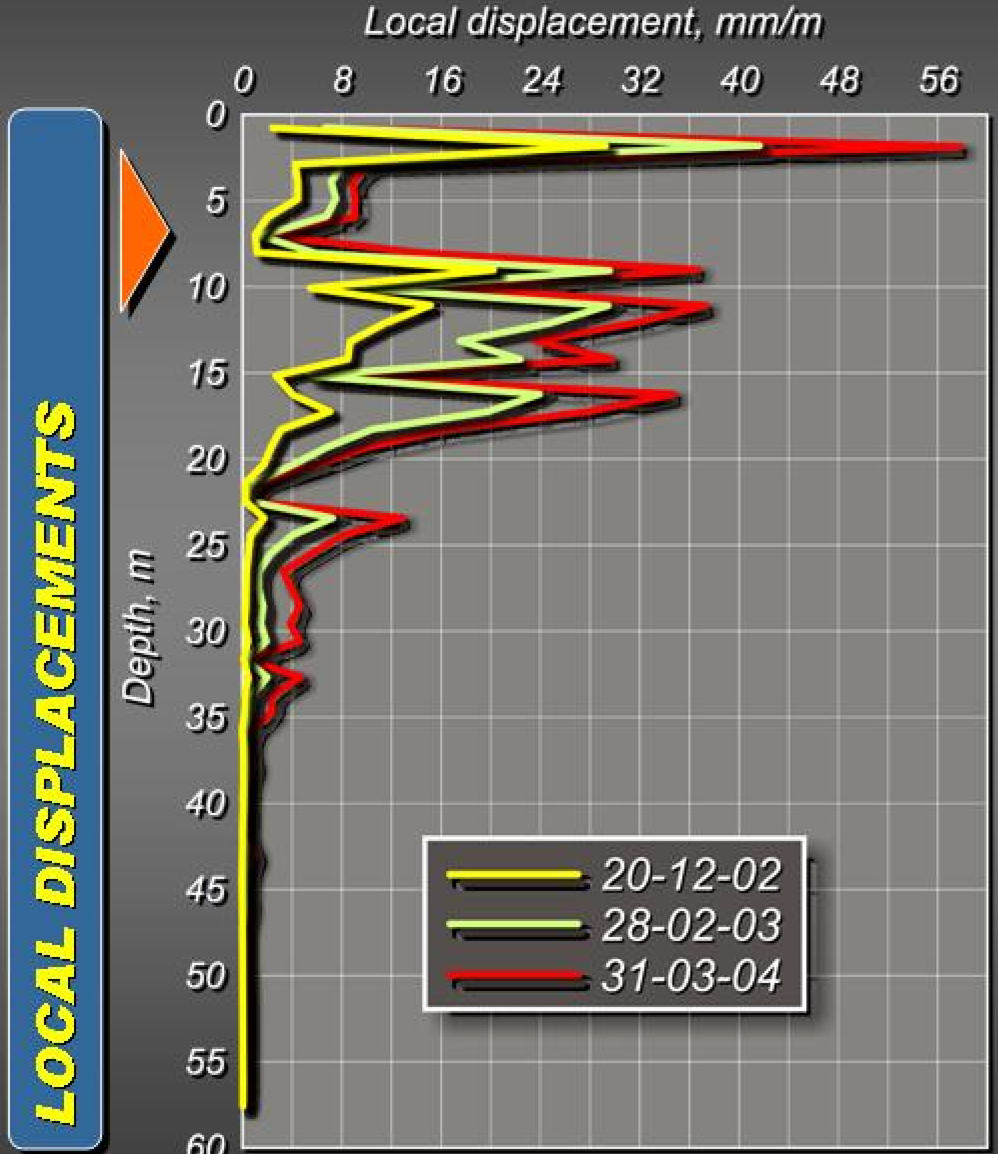
TRIAL EMBANKMENT: PORE PRESSURE FROM CASAGRANDE's PIEZOMETERS

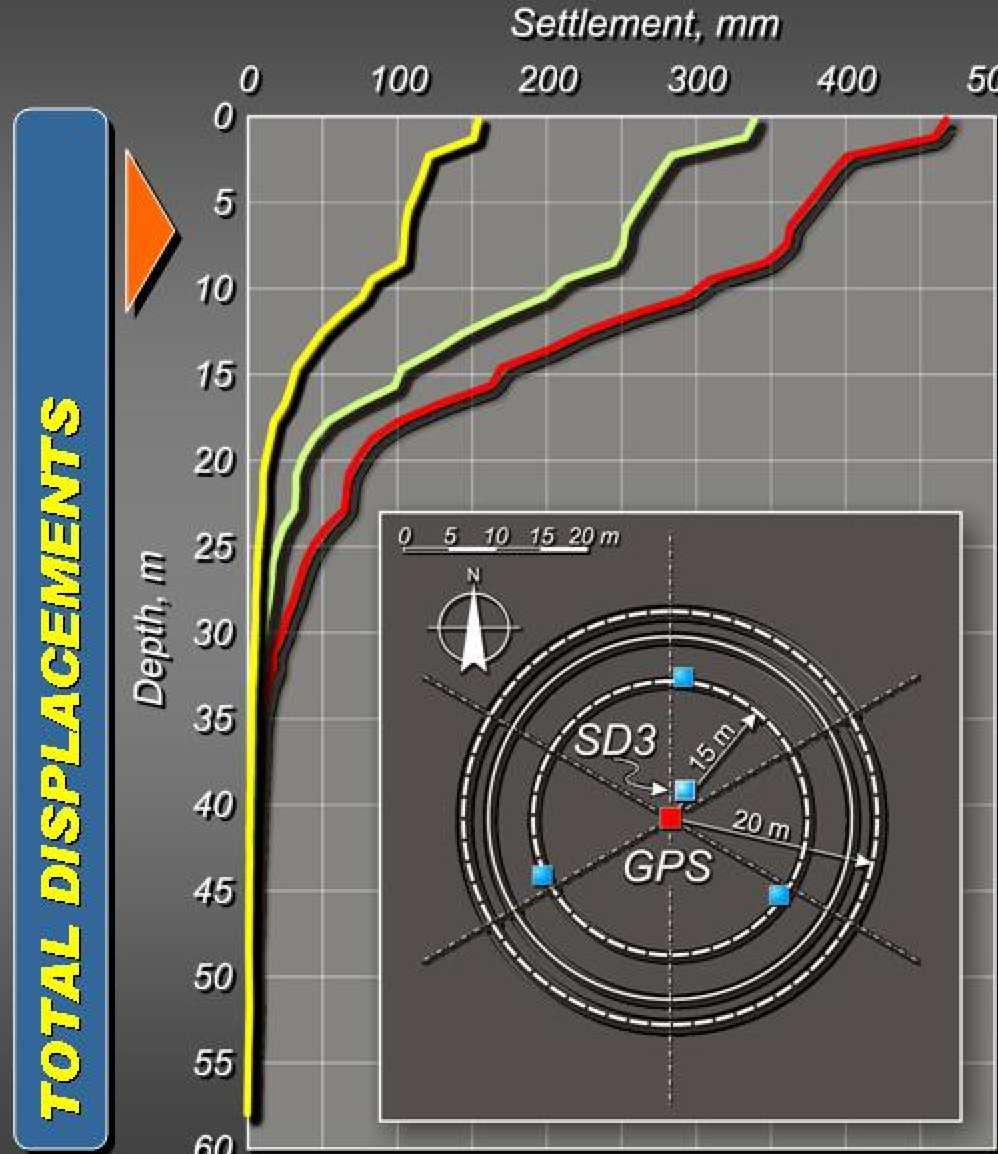


Ricceri et al. (2004)

TRIAL EMBANKMENT: VERTICAL DISPLACEMENTS

Sliding Deformeter n°3 – Ricceri et al. (2004)

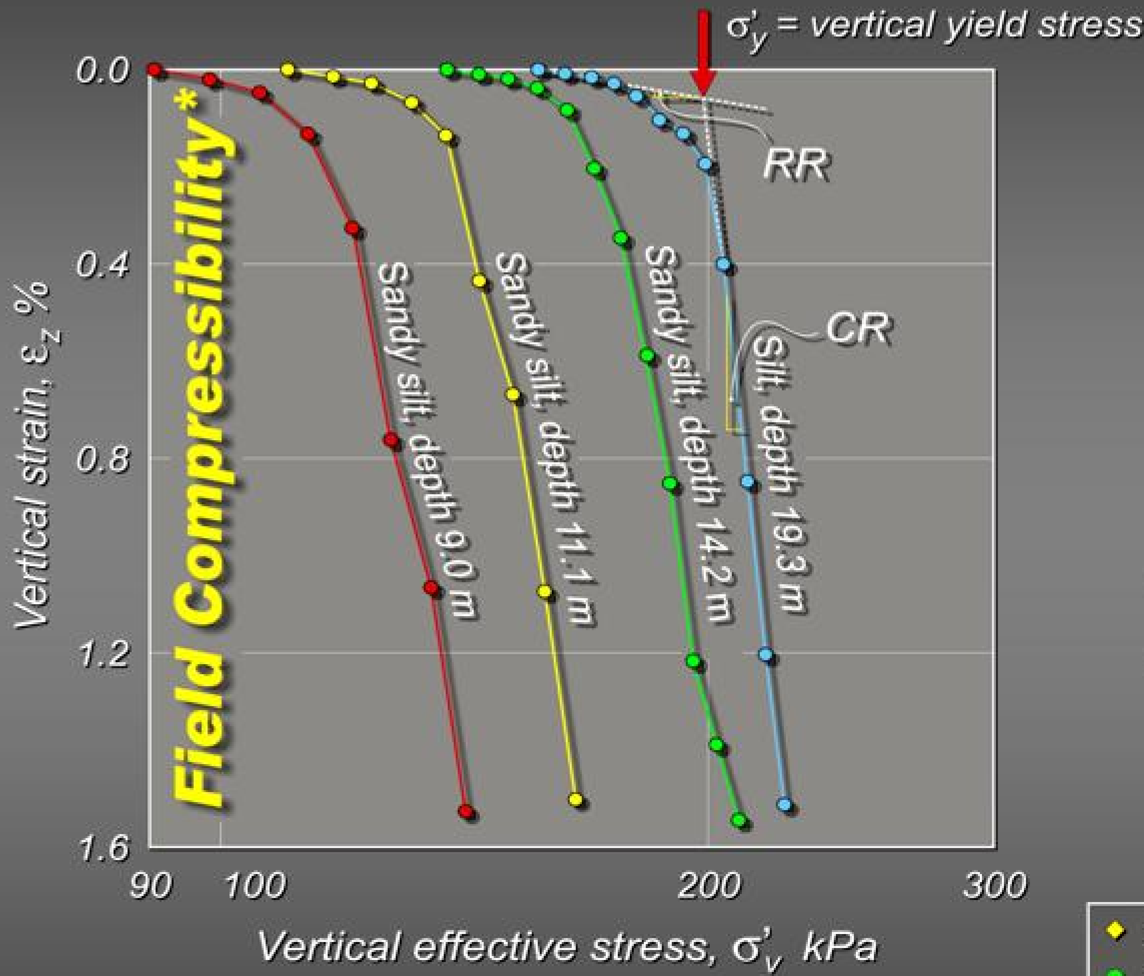


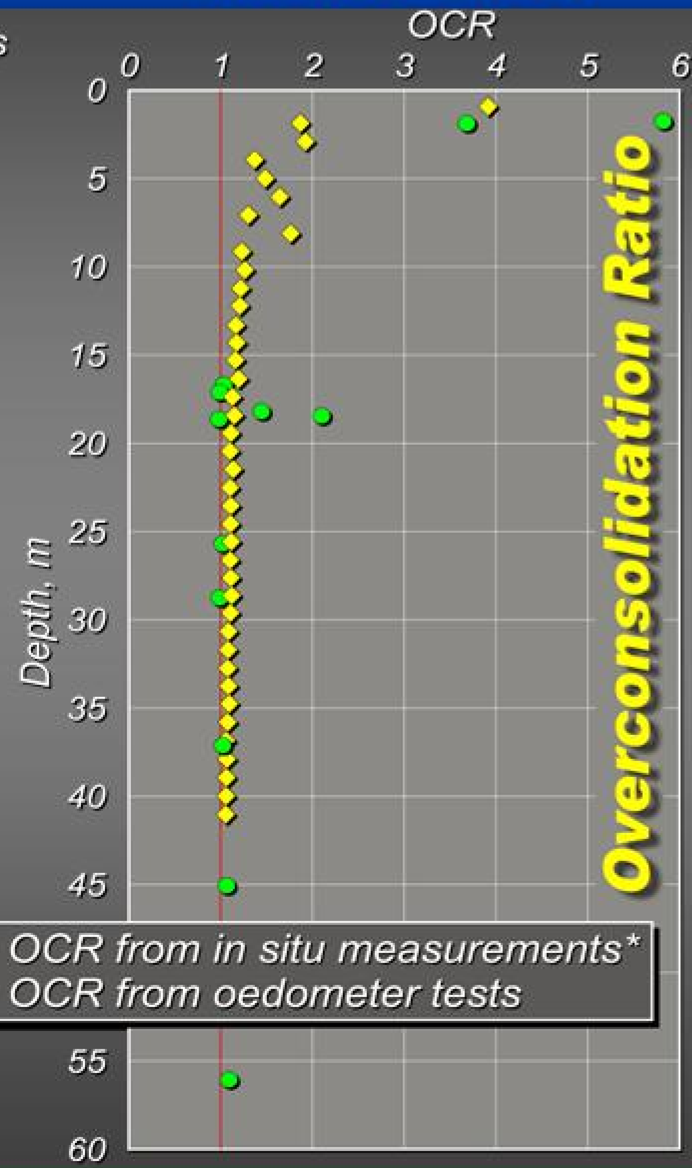


LIDO INLET - TRIAL EMBANKMENT

Subsoil stress history

Ricceri et al. (2004)





(*) From sliding deformeter n° 3
under center of the embankment

RECOMPRESSION RATIO and SECONDARY COMPRESSION COEFFICIENT
IN SITU vs. LABORATORY

SOIL TYPE*	$\dfrac{RR\ (lab)}{RR\ (in\ situ)}$	$\dfrac{C_{\alpha\varepsilon}\ (in\ situ)}{C_{\alpha\varepsilon}\ (lab)}$
SM and SP	**2.5 to 4.0**	**0.74 to 0.95**
ML and CL	**4.0 to 5.0**	**1.52 to 1.56**

$$RR = \frac{d\varepsilon_v}{d(\log_{10} \sigma'_v)}$$

Recompression ratio

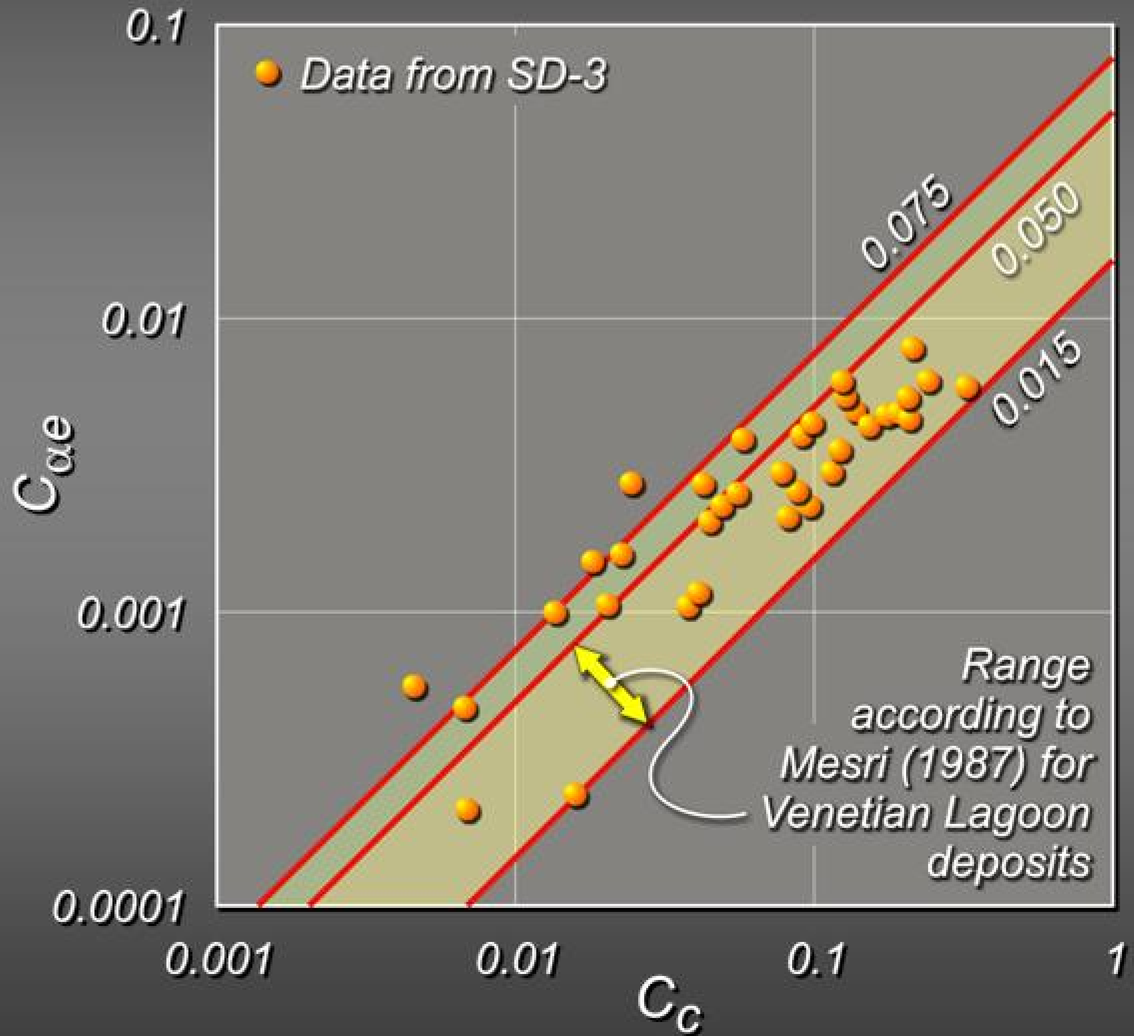
$$C_{\alpha\varepsilon} = \frac{d\varepsilon_v}{d(\log_{10} t)}$$

Secondary compression coefficient

(*) Unified Soil Classification System ASTM 2487

PRIMARY AND SECONDARY COMPRESSIBILITY MEASURED IN SITU

Ricceri et al. (2004)



$$C_c = \frac{de}{d(\log_{10} \sigma'_v)}$$

Coefficient of primary compression

$$C_{\alpha e} = \frac{de}{d(\log_{10} t)}$$

Coefficient of secondary compression

MALAMOCCO BARRIER
SIMPLIFIED SITE CHARACTERIZATION

Layer	γ kN/m^3	ν'	G_0** bar	φ'_{cv}
D	18.7	0.30	911	32°
E	19.1	0.30	985	33°
E’	18.8	0.35	476	28°

- D: Clayey silt and sandy silt
- E: Fine locally silty sand
- E’: Clayey and sandy silt

(*) Original sea bed at elev. -14.0 to -16.0 below msl
Unloading due to dredging $95 \le \sigma'_v \le 112$ kPa

(**) From CHT, at p’ = 1 bar

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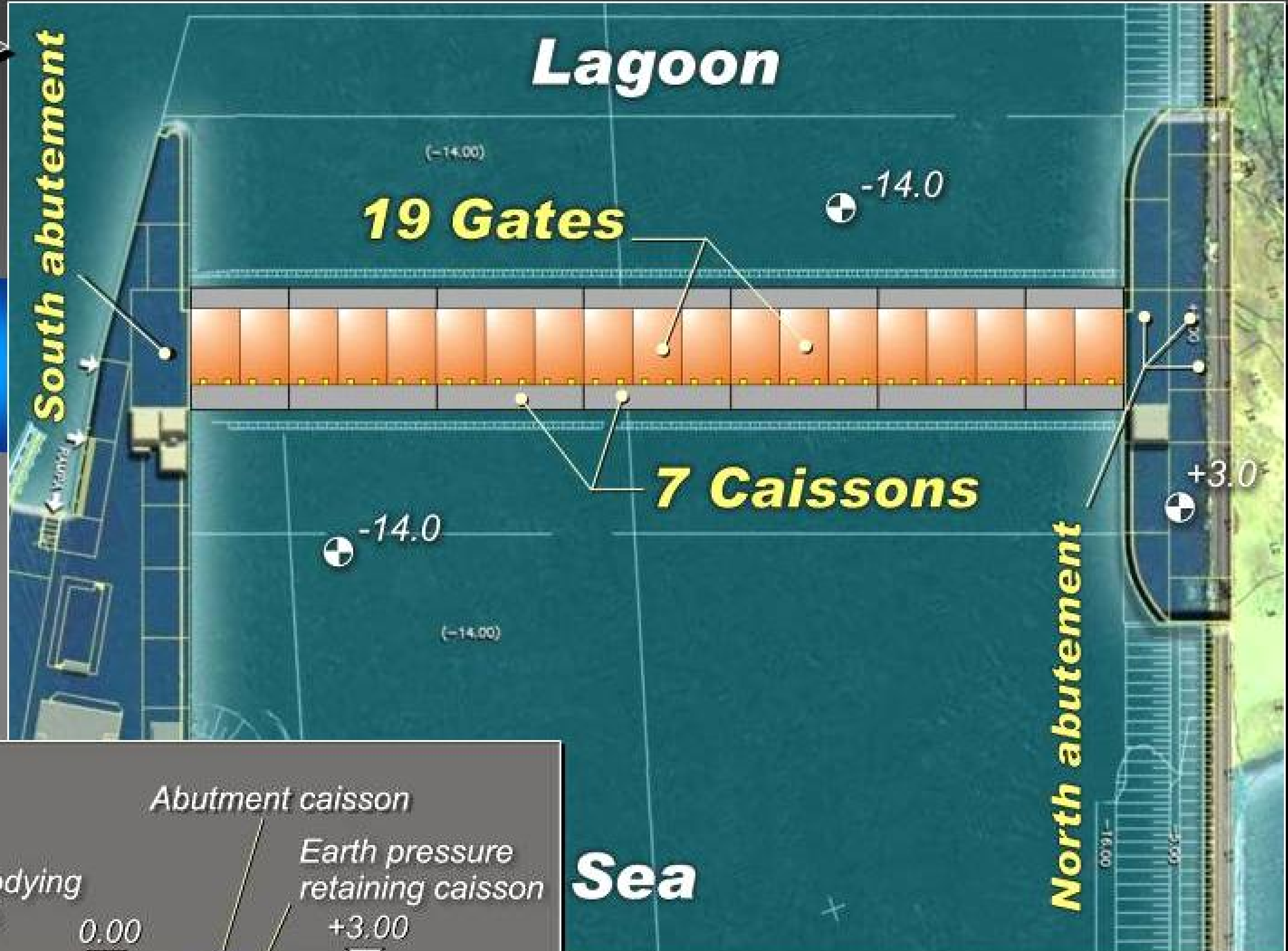
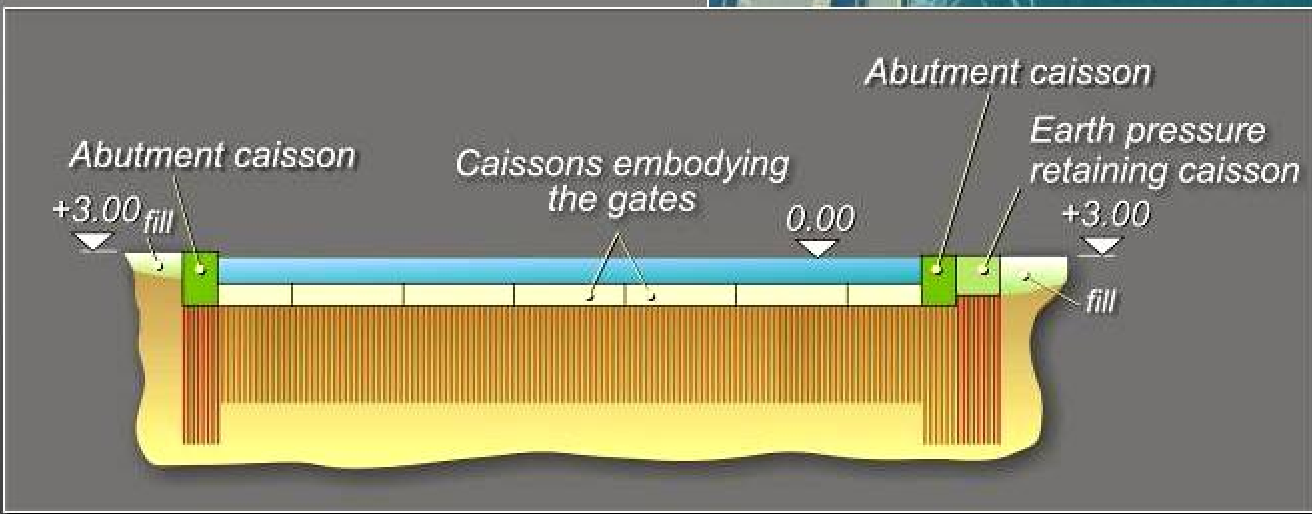
Plan view

MALAMOCCO BARRIER

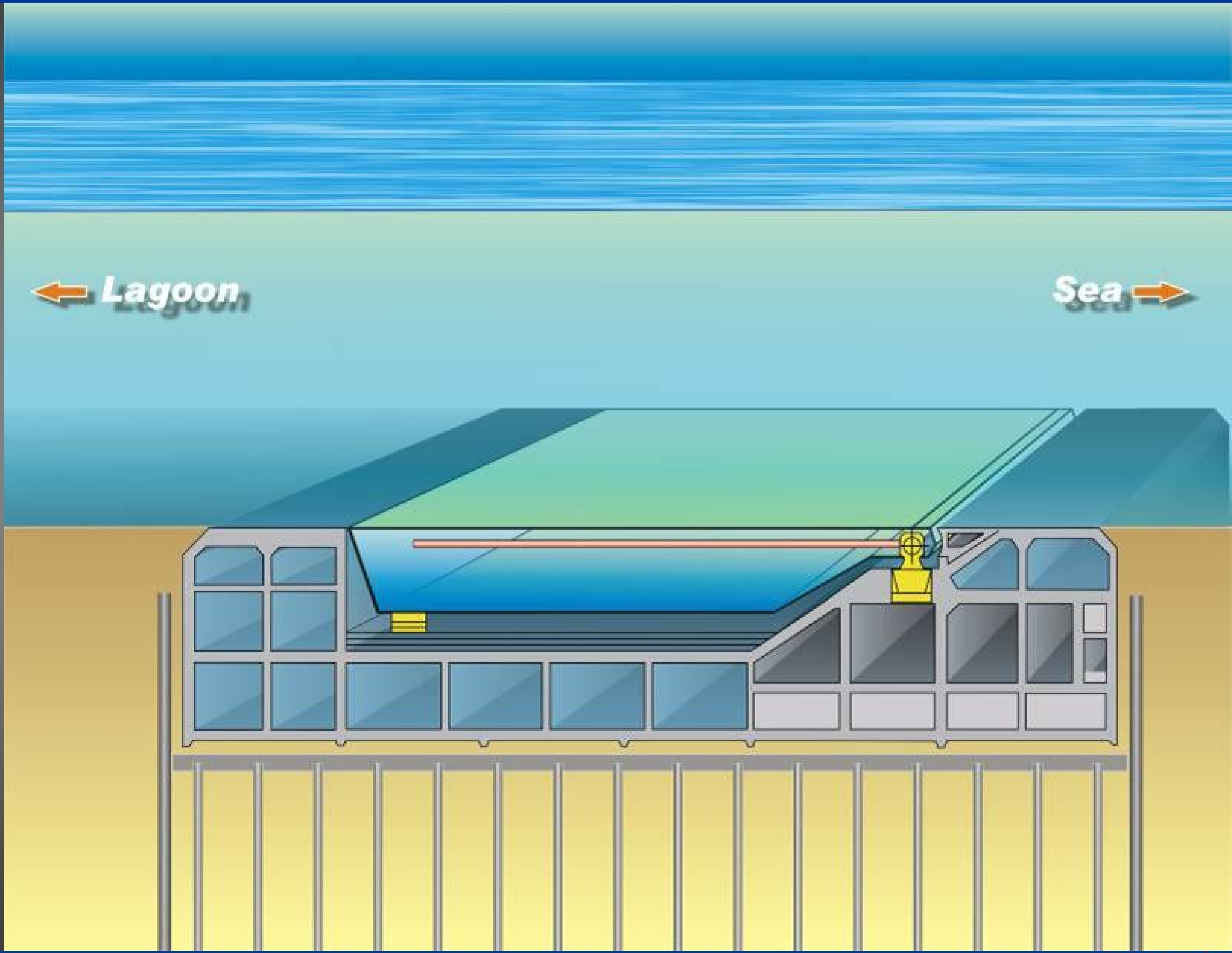




Schematic cross-section

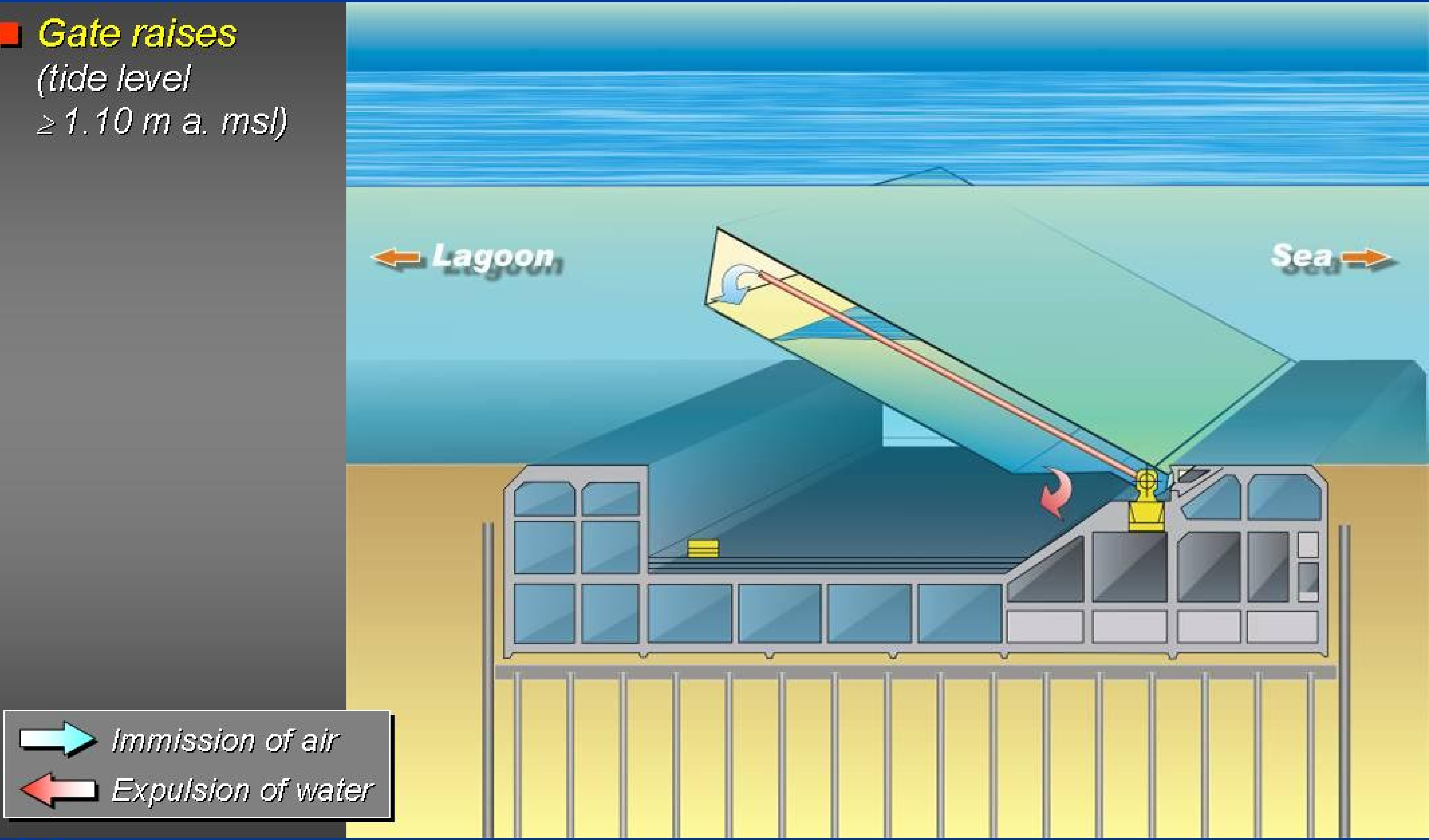
FLOODGATES: OPERATIONAL SCHEME

- *Gate quiescent*
  (inlet open)



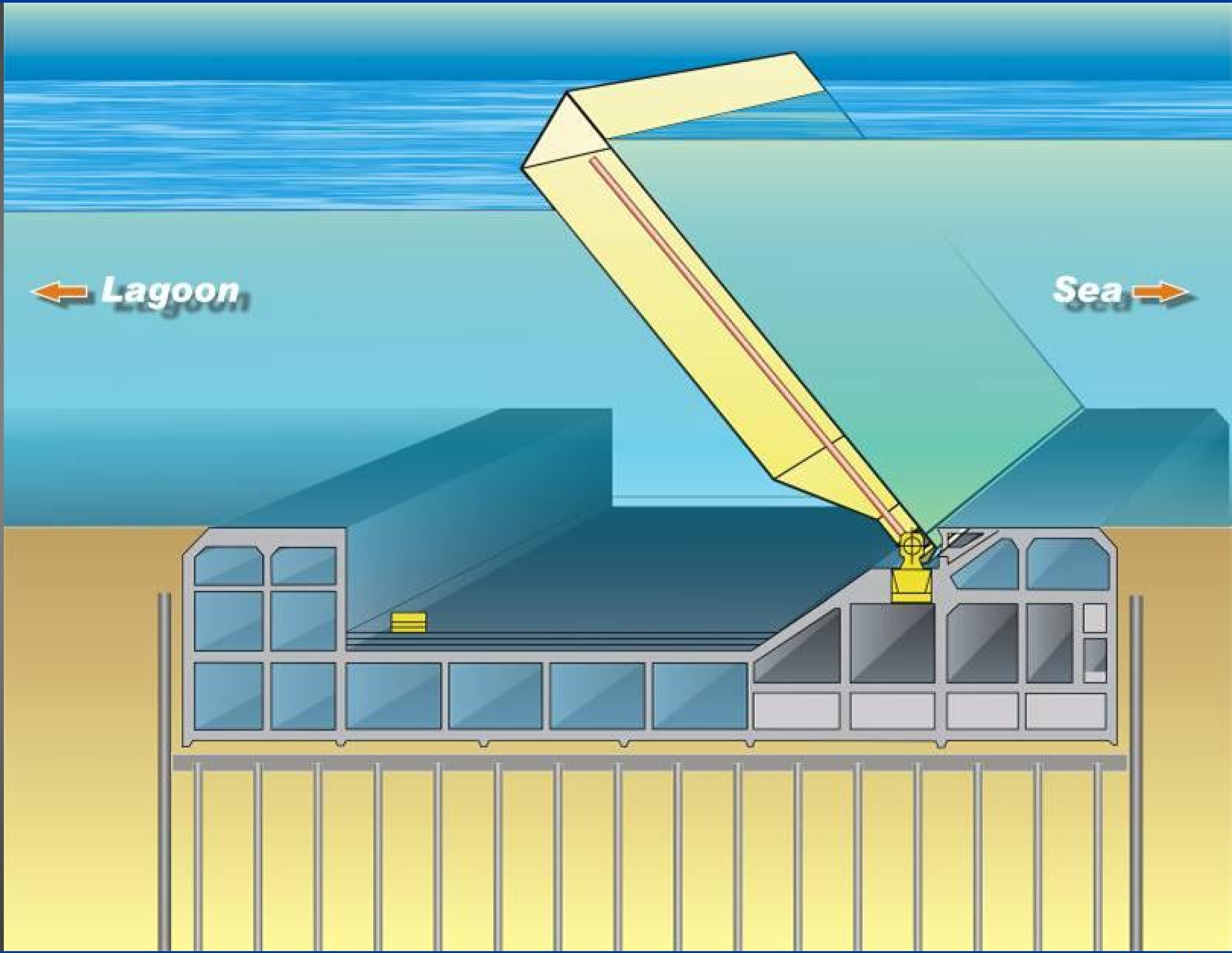
FLOODGATES: OPERATIONAL SCHEME

- *Gate raises (tide level ≥ 1.10 m a. msl)*



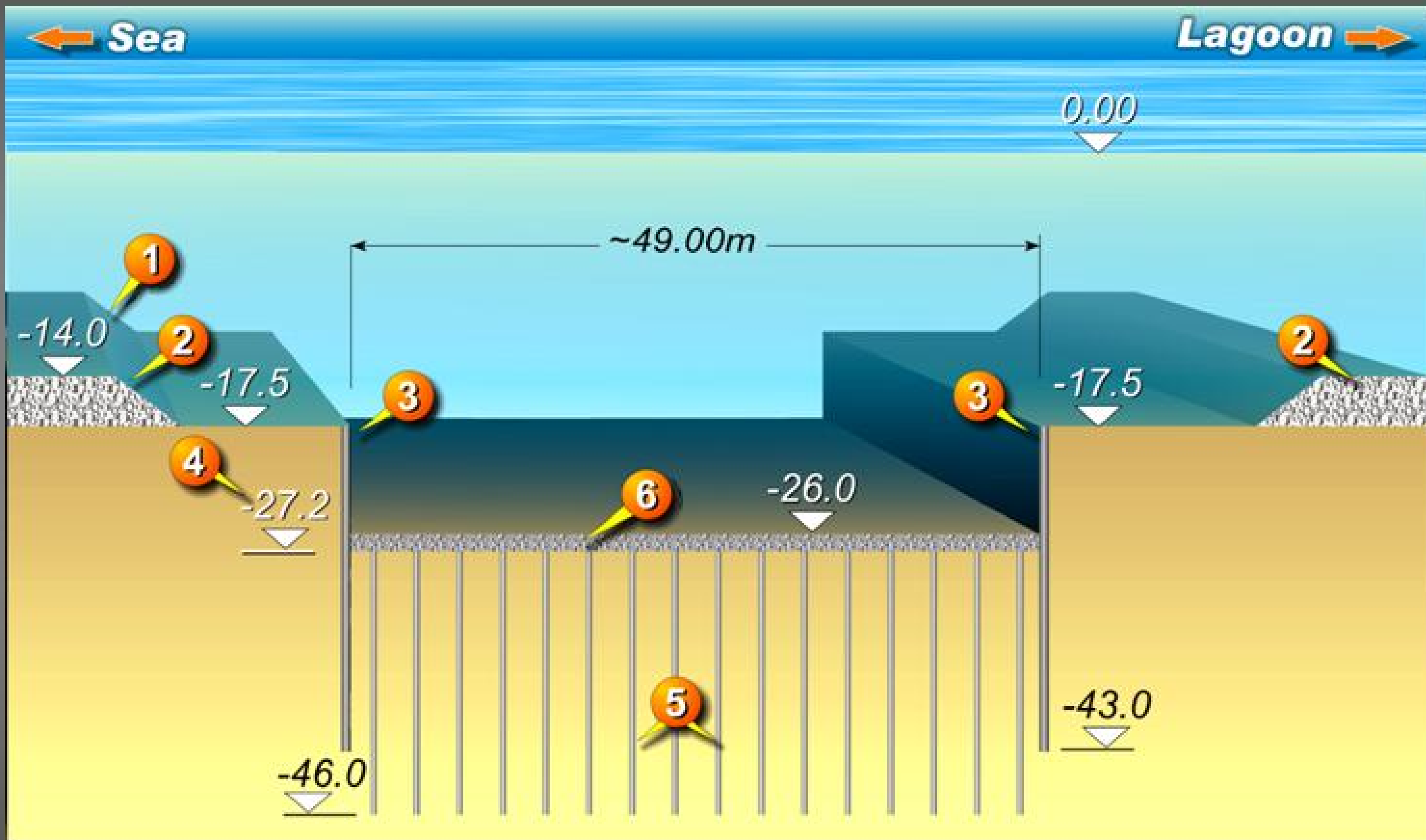
FLOODGATES: OPERATIONAL SCHEME

- *Gate in operation*
  (inlet closed)



MALAMOCCO BARRIER – PREPARATION OF CAISSONS FOUNDATION

CONSTRUCTION SEQUENCE (1)



1. Dredging to elev. -17.5 b.m.s.l.
2. Placement of granular fill
3. Sheet pile driving
4. Trench dredging to elev. -27.2 b.m.s.l.
5. Piles driving
6. Placement of granular fill between sheet piles

MALAMOCCO BARRIER – PREPARATION OF CAISSONS FOUNDATION

CONSTRUCTION SEQUENCE (2)

7 8 Caisson placement on four temporary plinths

9 Levelling the caisson by means of hydraulic jacks

10 Caisson's balasting

11 Levelling the caisson by means of hydraulic jacks

12 Grouting the space between caisson's bottom 7 and granular fill 6

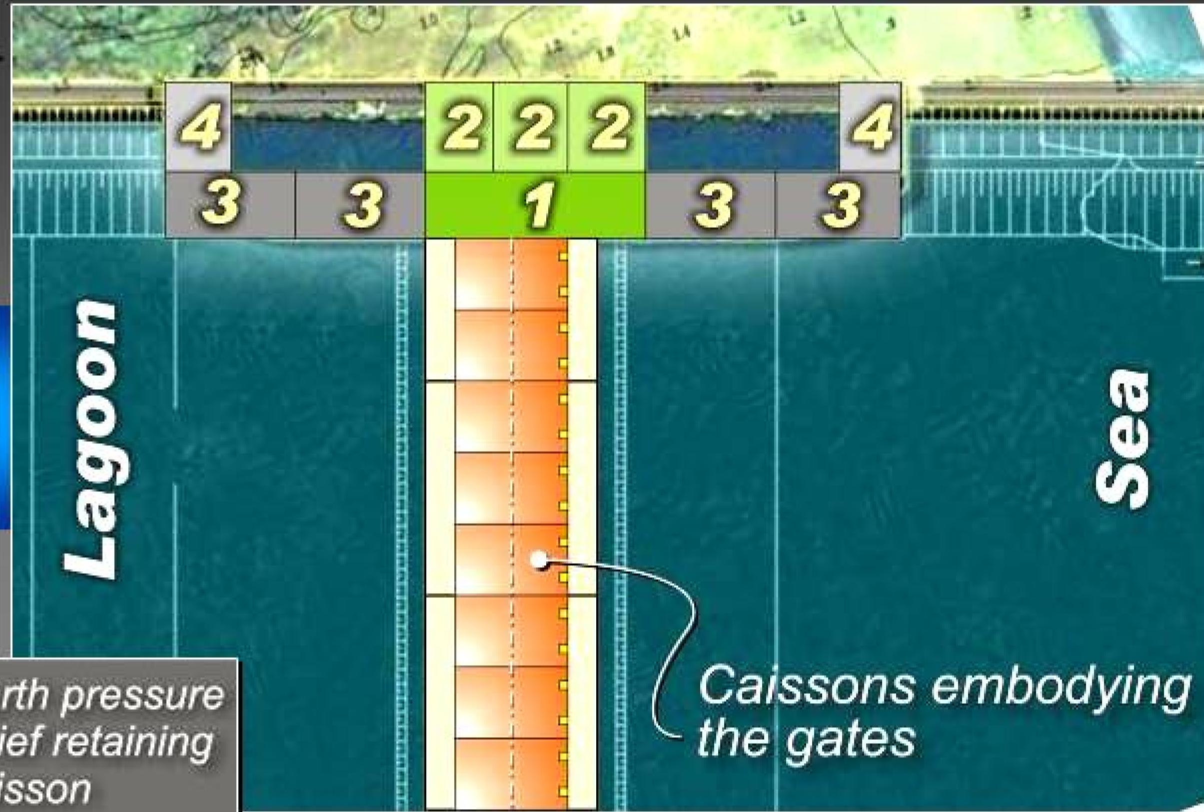
MALAMOCCO BARRIER – SEA BED PROTECTION

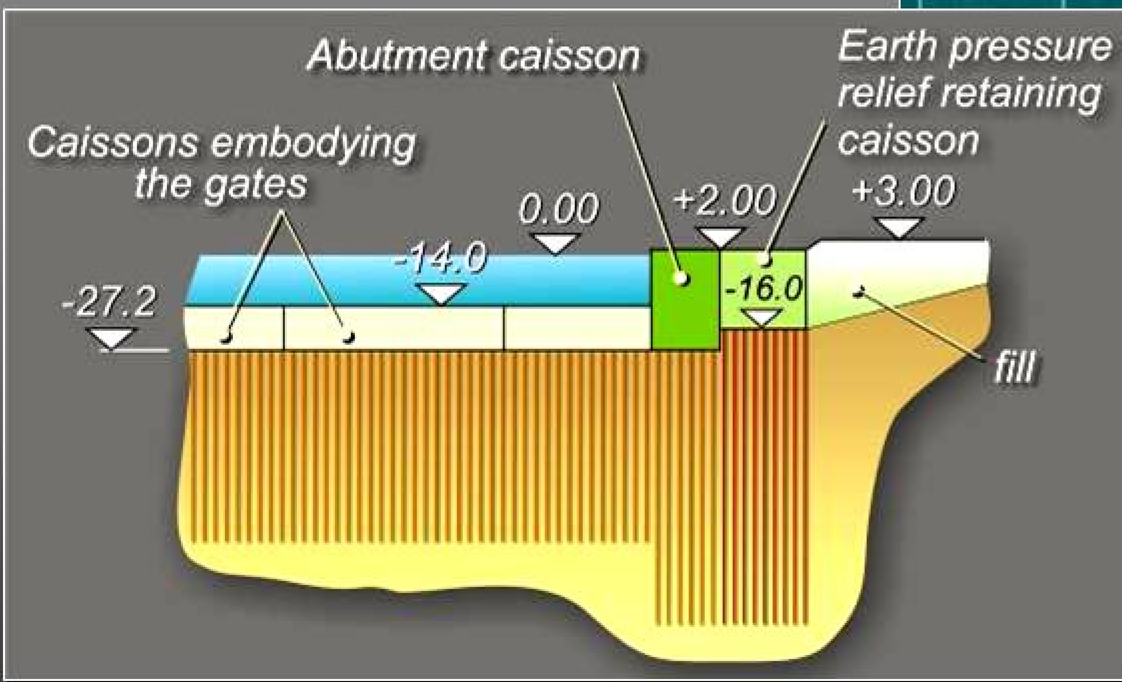
CLASS	Rockfill Weight, kN
A	10 to 30
B	3 to 10
C	0.6 to 3

CROSS SECTION

Plan view

MALAMOCCO BARRIER
NORTH ABUTMENT





1 Abutment caisson

2 Earth relief caisson

3 Lateral caisson

4 Wing caisson

Cross-section

Caissons embodying the mobile gates

Tolerable differential movements

- *Reduction of horizontal distance between gates embodied in two adjacent caissons, $\simeq$ 140 mm**
- *Slope of Crane's rails, $\simeq$ 1%*
- *Movement causing decompression of "GINA" joint between two adjacent caissons, $\simeq$ 30mm**

Above values include both differential caissons settlements and construction's imperfection

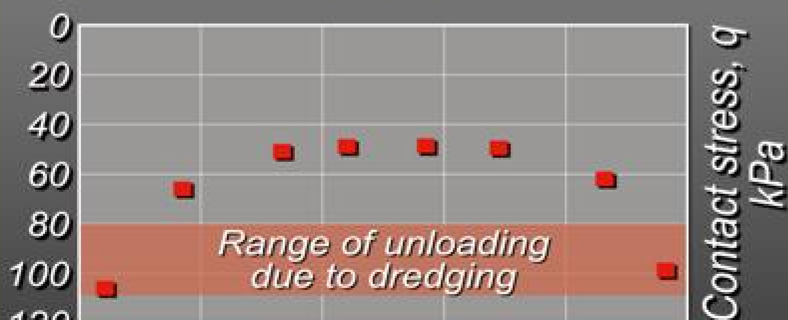
- ***Most important: horizontal distance between two adjacent gates*****

(*) Rubber joint of large dimensions, allowable value 40mm
(**) Design value, 150 to 200mm

MALAMOCCO BARRIER ON SETTLEMENT REDUCING PILES*
COMPUTED DISPLACEMENTS**

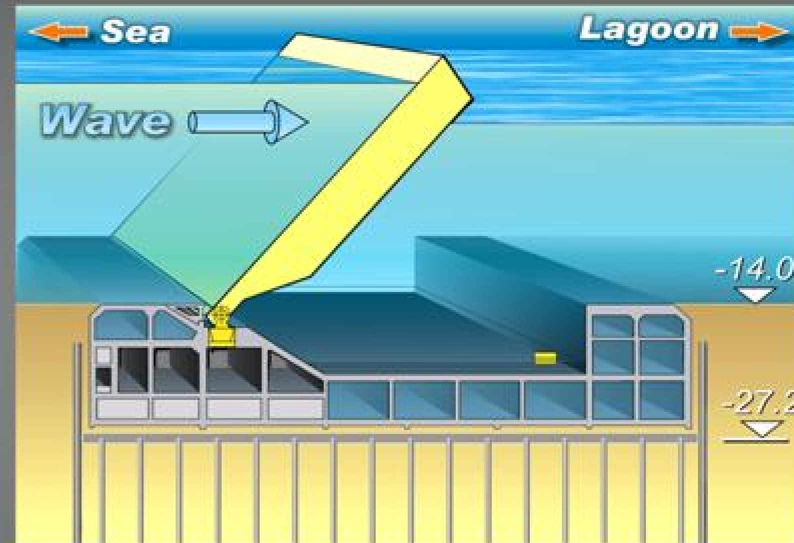
GATE CLOSED, CRANE IN OPERATION

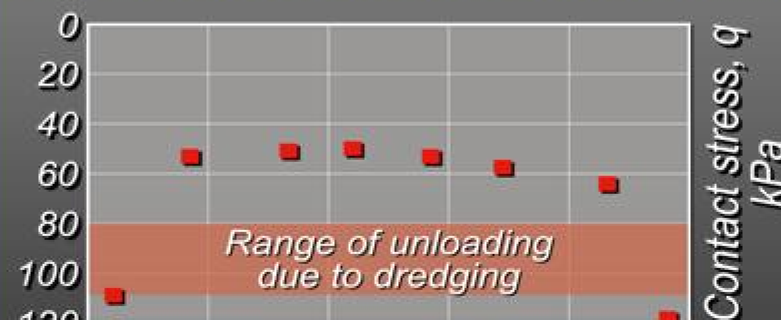
SEA	LAGOON
s_v = 44.0 mm	s_v = 41.5 mm
s_h = 0	



GATE OPEN, WAVES ACTION

SEA	LAGOON
s_v = 36.9 mm	s_v = 45.0 mm
s_h = 25.6 mm	





(*) L ≅ 19m long - (**) FE-2D elastoplastic analyses using PLAXIS code

BARRIERS FOUNDATIONS

- ***Except abutments' caissons, compensated foundations*** $(q \leq \sigma'_v)$
- ***Design guided by settlements consideration***
- ***Settlements induced by reclamation fills, hence importance of construction sequence***
- ***Need to predict long term settlements, creep, waves, high tides action, …….***
- ***Importance of preliminary trial fields to optimize construction techniques***

CAISSONS FOUNDATIONS: TRIAL FIELD

- **17 JET GROUTED COLUMNS**

  *Installed using mono-fluid, two-fluid and three-fluid method, $10 \leq L \leq 38m$, $1 \leq D \leq 1.4m$; 14 installed onshore and 3 offshore**

- **13 INSTRUMENTED END-CLOSED DRIVEN STEEL TUBULAR PILES***

  $D = 0.406m$, $t = 16mm$, $L = 18m$, except one having $L = 42m$

- **13 R.C. PREFABRICATED TAPERED PILES***

  $D_{min} = 0.33m$, $D_{max} = 0.42m$, $L = 18m$

To be used as settlement reducing piles

(*) installed offshore, sea bottom at –13.5 m b. msl

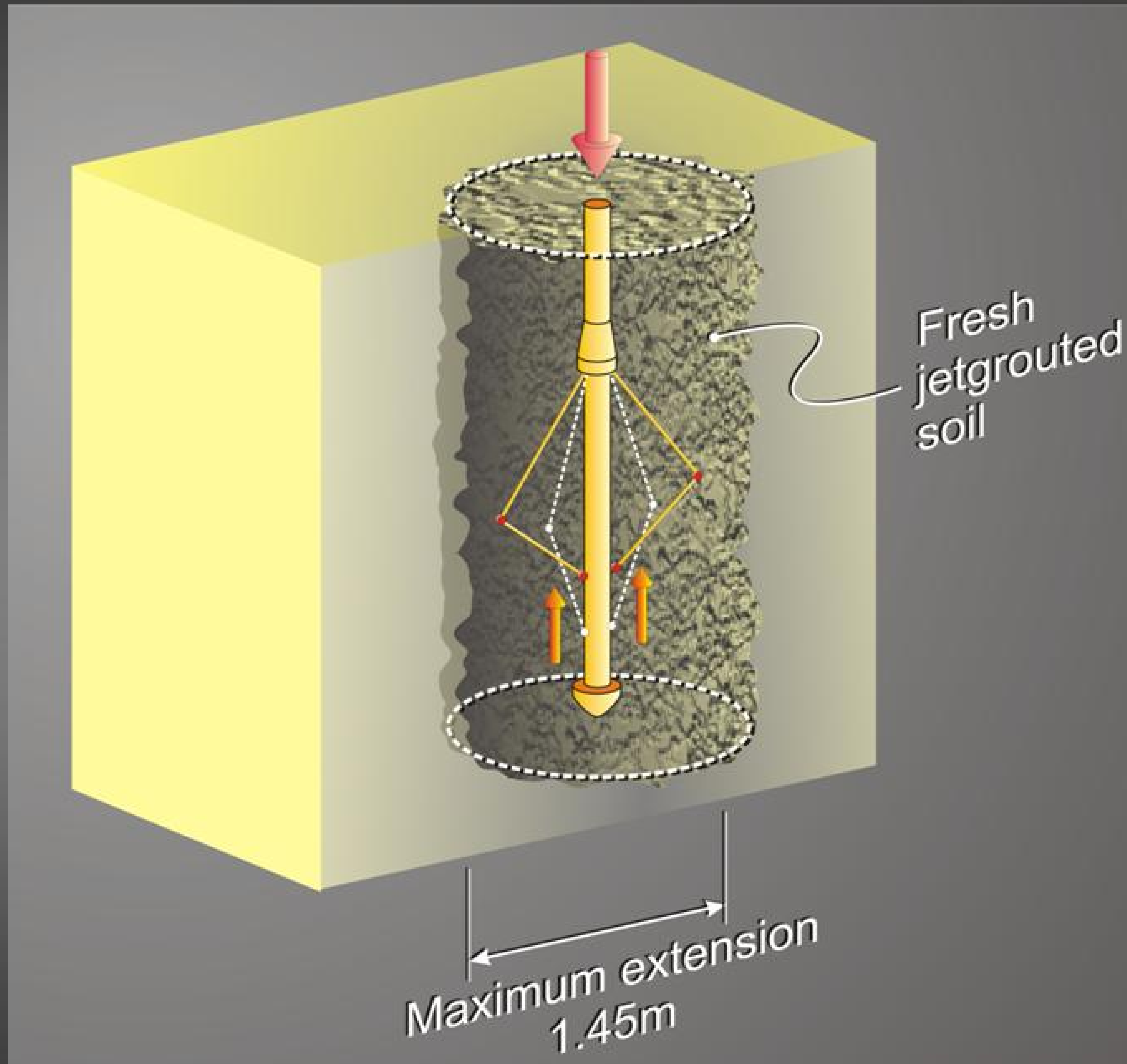
ON-SHORE JETGROUTING TRIAL FIELD

Columns JG8 and JG11 will be extracted from the ground

Quality control activities

- Specific energy used to carry out each column
- Volume of injected fluid (water, cement mix)
- Outflow volume
- Deviation from vertical
- Column diameter (mechanical calyper, seismic tomography)
- Continuous coring (continuity of cementation, strength)

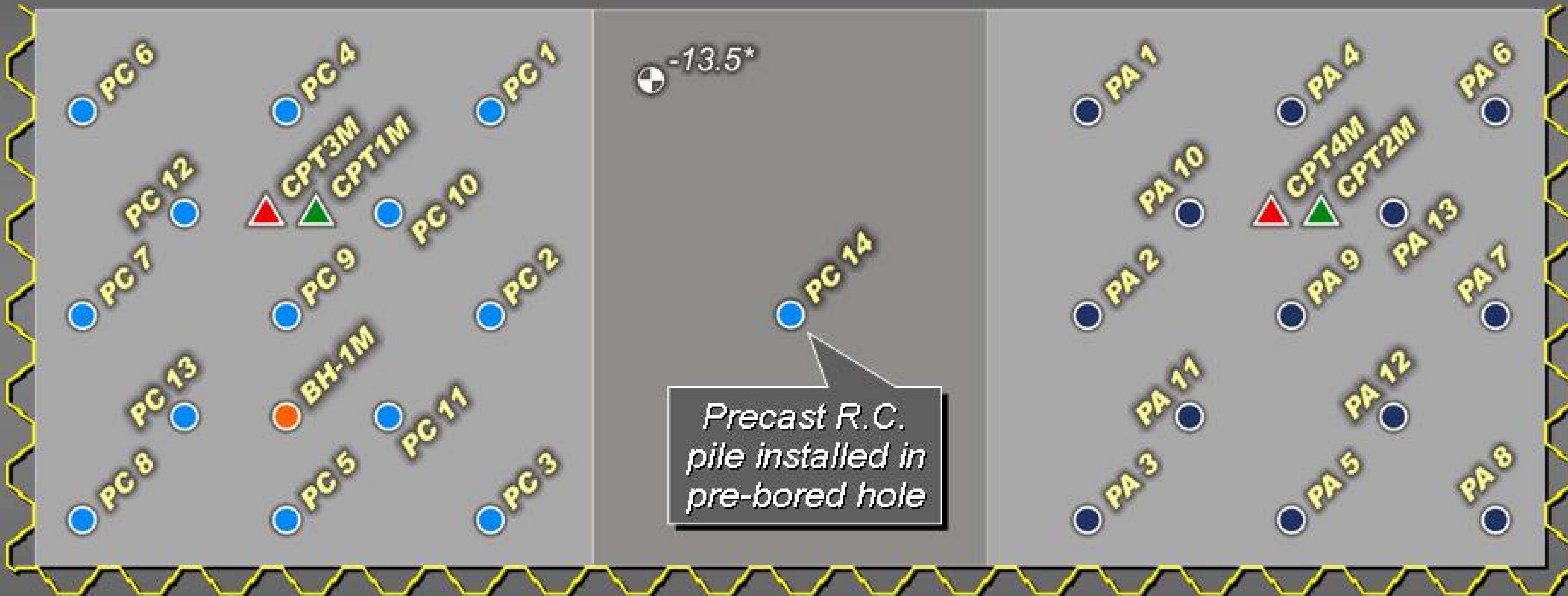
ESTIMATE OF JETGROUTED COLUMNS DIAMETER USING MECHANICAL CALYPER



OFF-SHORE TRIAL FIELD: PLAN VIEW

13 precast instrumented R.C. tapered piles
D_{min}=0.33m; D_{max}=0.42m; L = 18m

13 instrumented, closed end steel piles
D = 0.406m; t = 16mm ; L = 18m



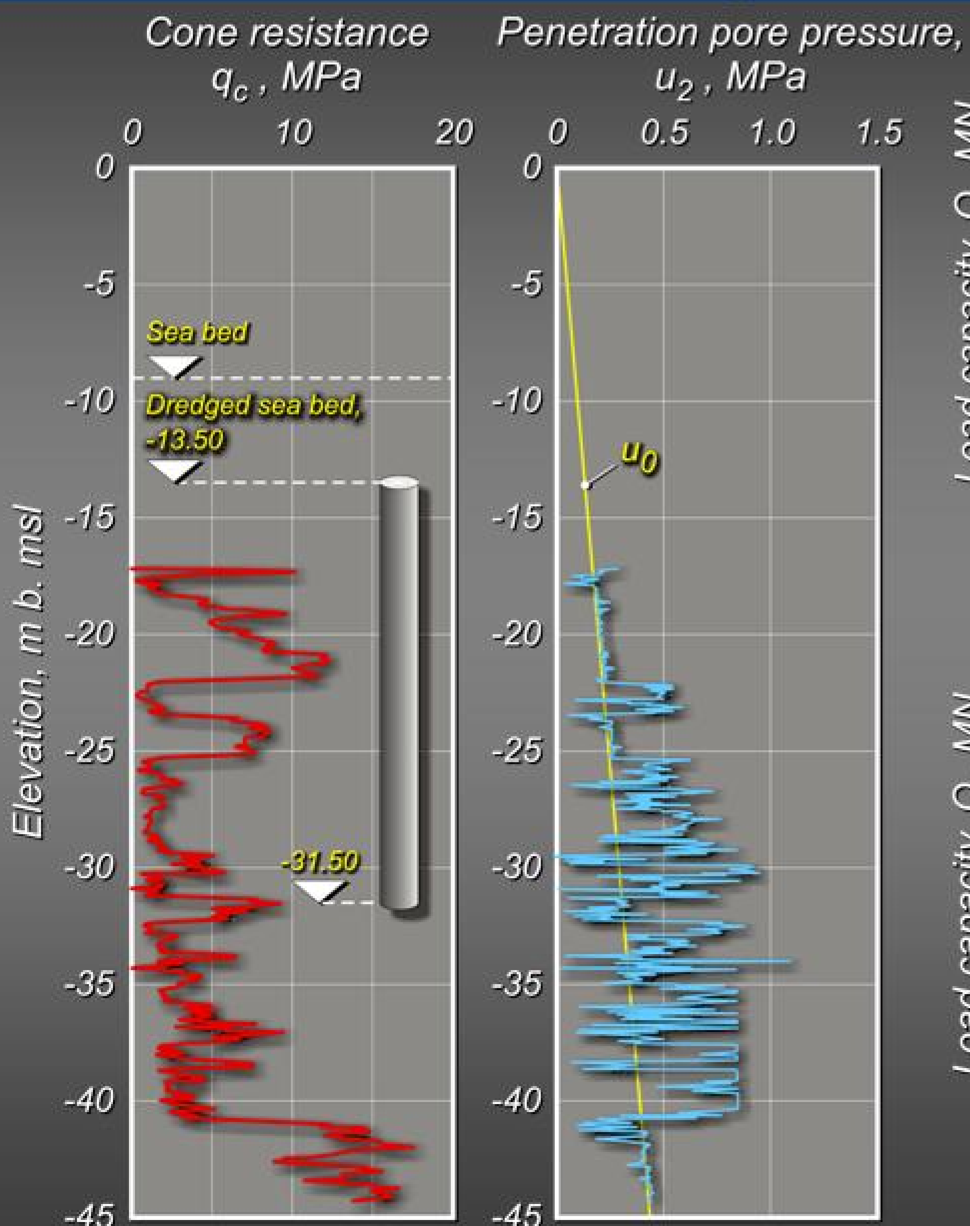
Larsen sheet pile, L=18m

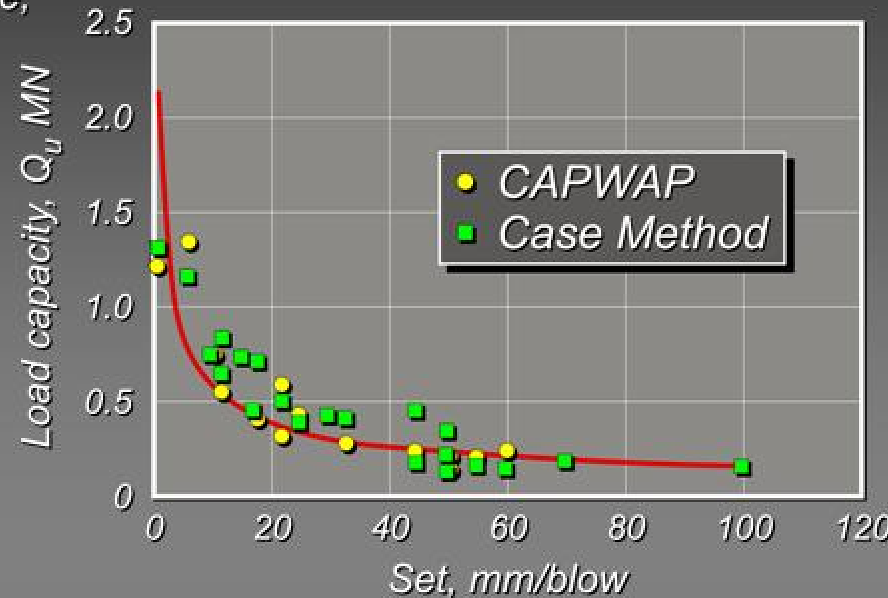
3 jetgrouted columns
1.2 ≤ D ≤ 1.4m ; L = 19m

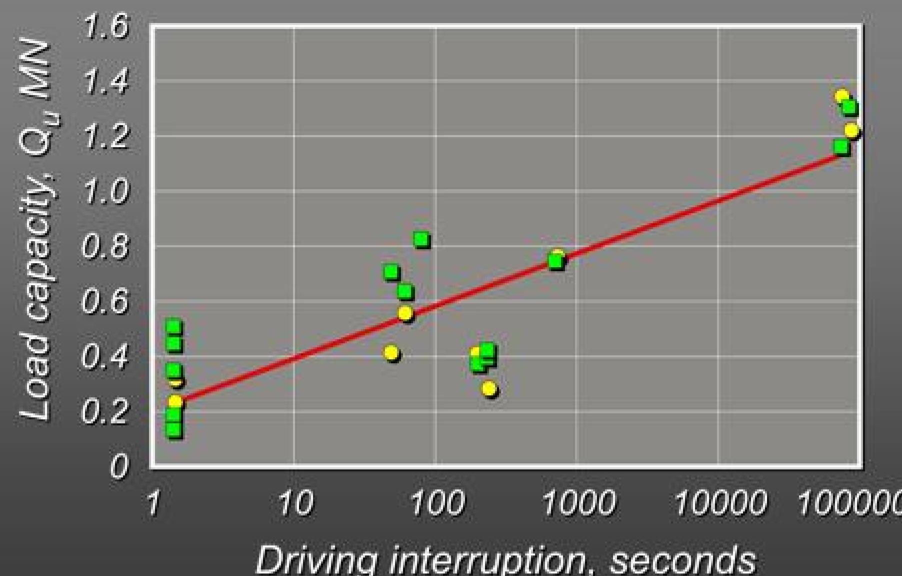
(*) Original sea bed at –7.0 b. msl

LOAD CAPACITY OF DRIVEN STEEL TUBULAR PILES

Closed-end, D_0 = 405 mm, t = 16 mm, L = 18 m







Lecture Outline

- Introductory remarks
- Protection from high tides
  - Historical background
  - Selected solution
- Lagoon subsoil
- Foundation problems
- **Closing remarks**

Closing Remarks

Challenging project imposing multidisciplinary approach:

- *Different branches of engineering, e.g.: Mechanical, Structural, Hydraulic, Geotechnical, Harbour, Earthquake,…….*
- *A variety of experts in Geology, e.g.: Geomorphology, Sedimentology, Paleontology, Neotectonics,…..*
- *Environmentalists, Biologists, Zoologists,……..*
- *Experts on Preservation and Restoration of monuments and Archeologists*

Closing Remarks

Geotechnical site characterization

- Complex depositional environment hence pronounced spatial heterogeneity
- Predominate sandy silts with alternation of silty sands and clayey silts
- Gradation and heterogeneity make undisturbed sampling difficult, hampering laboratory tests relevance
- High relevance of in situ testing (SPT, CPTU, DMT) and especially geophysical tests, geotechnically oriented (CHT, S-CPTU, S-DMT)
- Paramount importance for design of large scale, instrumented embankment carried out by University of Padova (Ricceri et al. , 2004)

PROJECT IN PROGRESS

- **Many complementary interventions accomplished, e.g.:**
  Arrest of environmental deterioration
  Raising level of insulae and embankments
  Coast line reinforced
  Jetties reconstruction
- **Malamocco and Chioggia breakwater:** under construction
- **Final design of barriers:** under way, expected completition: second half year 2006
- **Prefabrication of barriers caissons:** to be started in autumn 2005

THREE BARRIERS FACT FILE:

- Expected time of completition: **2011**
- Estimated costs: **6.5** to **7.0** billions US$
- Construction assigned to a **General Contractors' Consortium**

CHALLENGE FOR GEOTECHNICAL ENGINEERS

- **PREDICTION OF LONG TERM SETTLEMENTS OWING TO:**

  Viscous deformation of foundation soils

  Accumulation of deformation (Ratcheting) caused by waves and high tides

  Influence of adjacent reclamation fills

- **HIGH VERTICAL AND HORIZONTAL LOADS ON ABUTMENTS' CAISSONS**

- **COMPLEX CONSTRUCTION SEQUENCE**

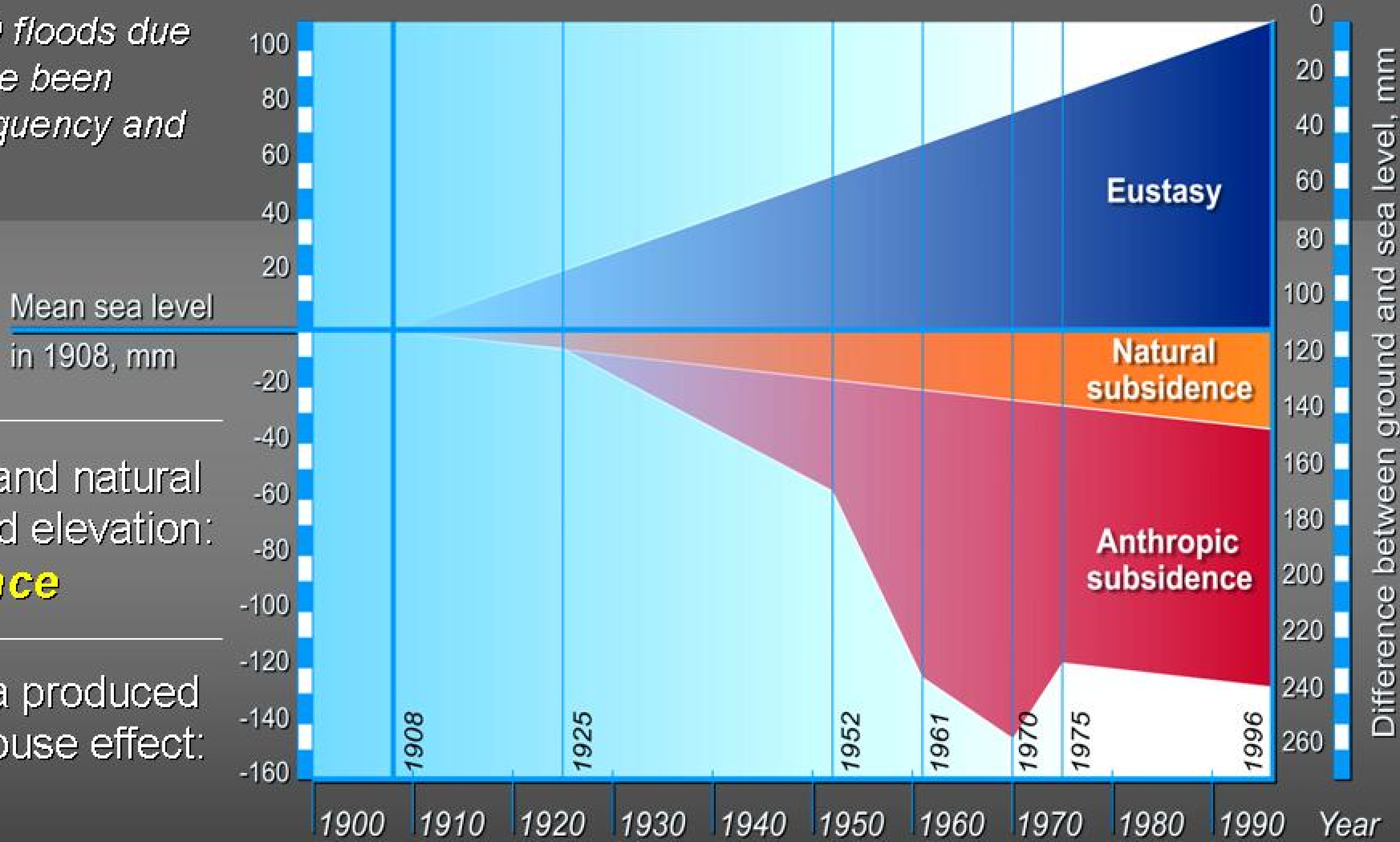
- **ISSUES RELATED TO QUALITY CONTROL AND ASSURANCE DURING CONSTRUCTION**


HYDRAULIC
MODEL OF
FLOOD GATES
(Scale 1:10)

VENICE: THE "SINKING" CITY

Since early 1900 floods due to high tides have been increasing in frequency and intensity

- Anthropic and natural drop in land elevation: ***Subsidence***
- Rise of sea produced by greenhouse effect: ***Eustasy***



Lecture Outline

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TRIAL EMBANKMENT: SURFACE SETTLEMENTS

High precision topographical survey

Ricceri et al. (2004)