FOURTH G.A. LEONARDS LECTURE - 2006

SAFEGUARDING VENICE LAGOON AGAINST HIGH TIDES

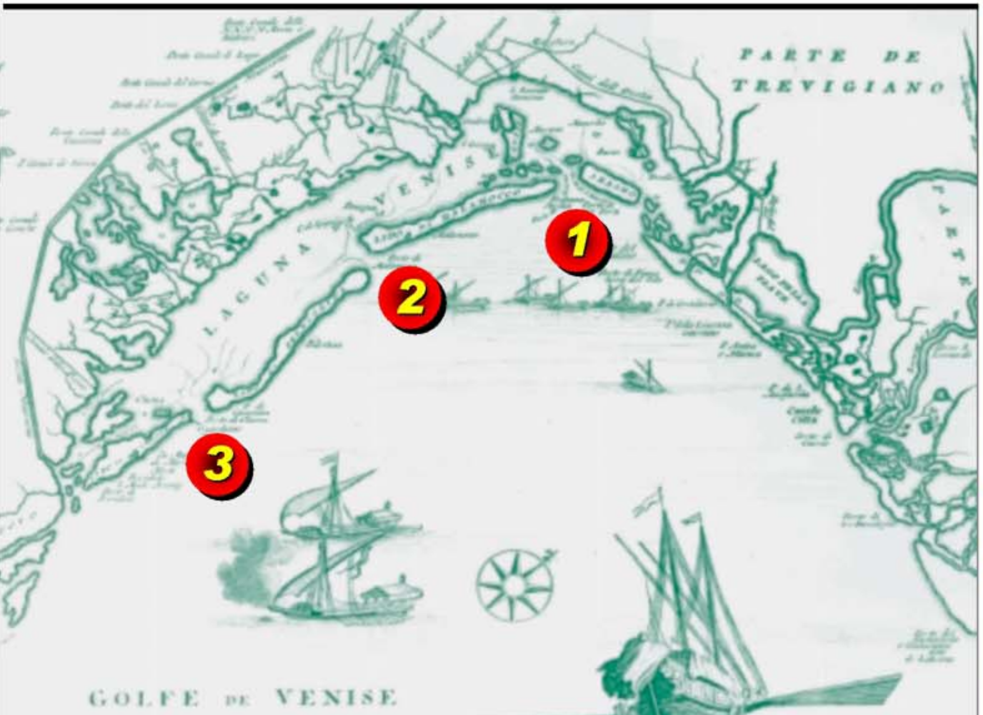
THE *MOSE PROJECT* AND RELATED GEOTECHNICAL PROBLEMS

Prof. Mike Jamiolkowski
Technical University of Torino

Lecture Outline

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

INLETS TO VENETIAN LAGOONS



Venetian Lagoon in 17th century

Venetian Lagoon today

1. LIDO INLET
2. MALAMOCCO INLET
3. CHIOGGIA INLET


Railway and highway bridge
Mainland
VENICE ISLAND
LIDO


Canal Grande

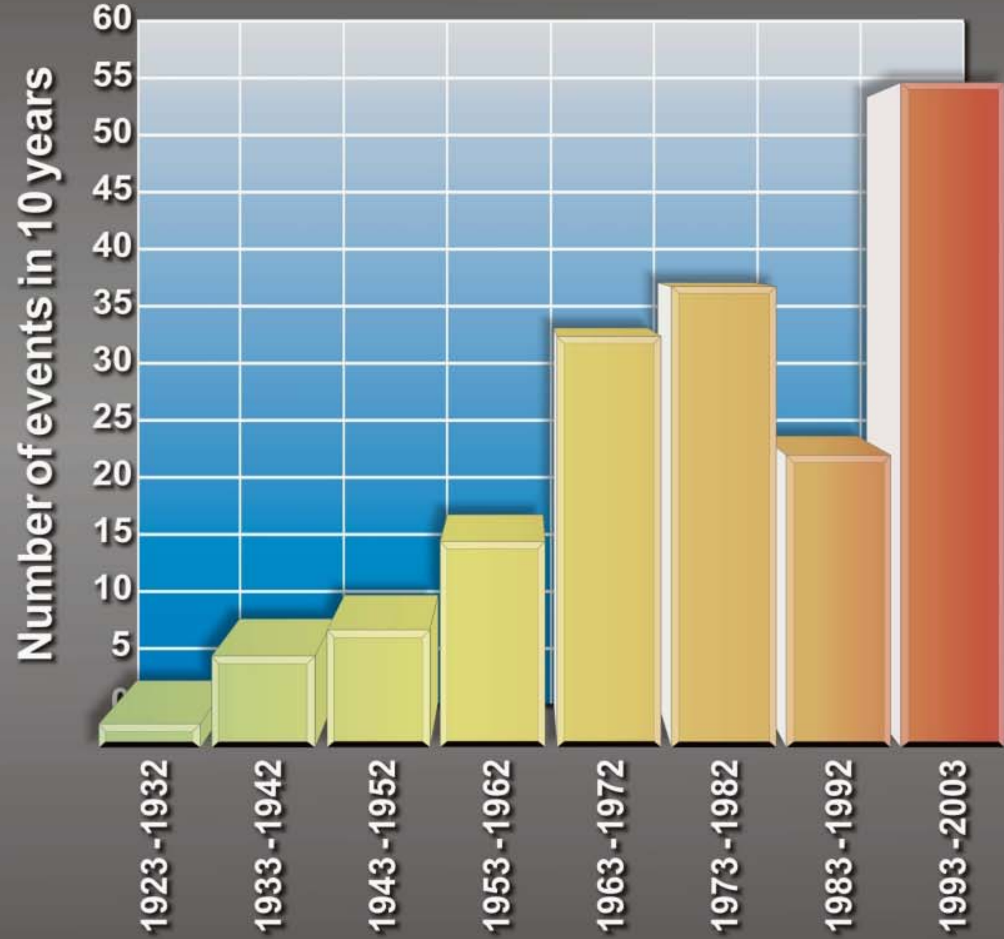
MAJOR HIGH TIDE EVENTS SINCE 1920's

Highest tides recorded*

December	2005	1.32
November	2004	1.38
January	2003	1.34
November	2002	1.47
November	2000	1.44
December	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



(*) As referred to Punta della Salute datum

Palazzo Ducale

Piazza S. Marco


PIAZZA SAN MARCO
DURING HIGH TIDE

G-150

PRT-01

VENICE:

A COMMERCIAL STREET DURING HIGH TIDE

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THE TIDE IN THE VENICE LAGOON

TYPICAL TIDE EXCURSION:

0.5 to 0.6 m, duration ~ 6 h

HIGH TIDE ("ACQUA ALTA"):

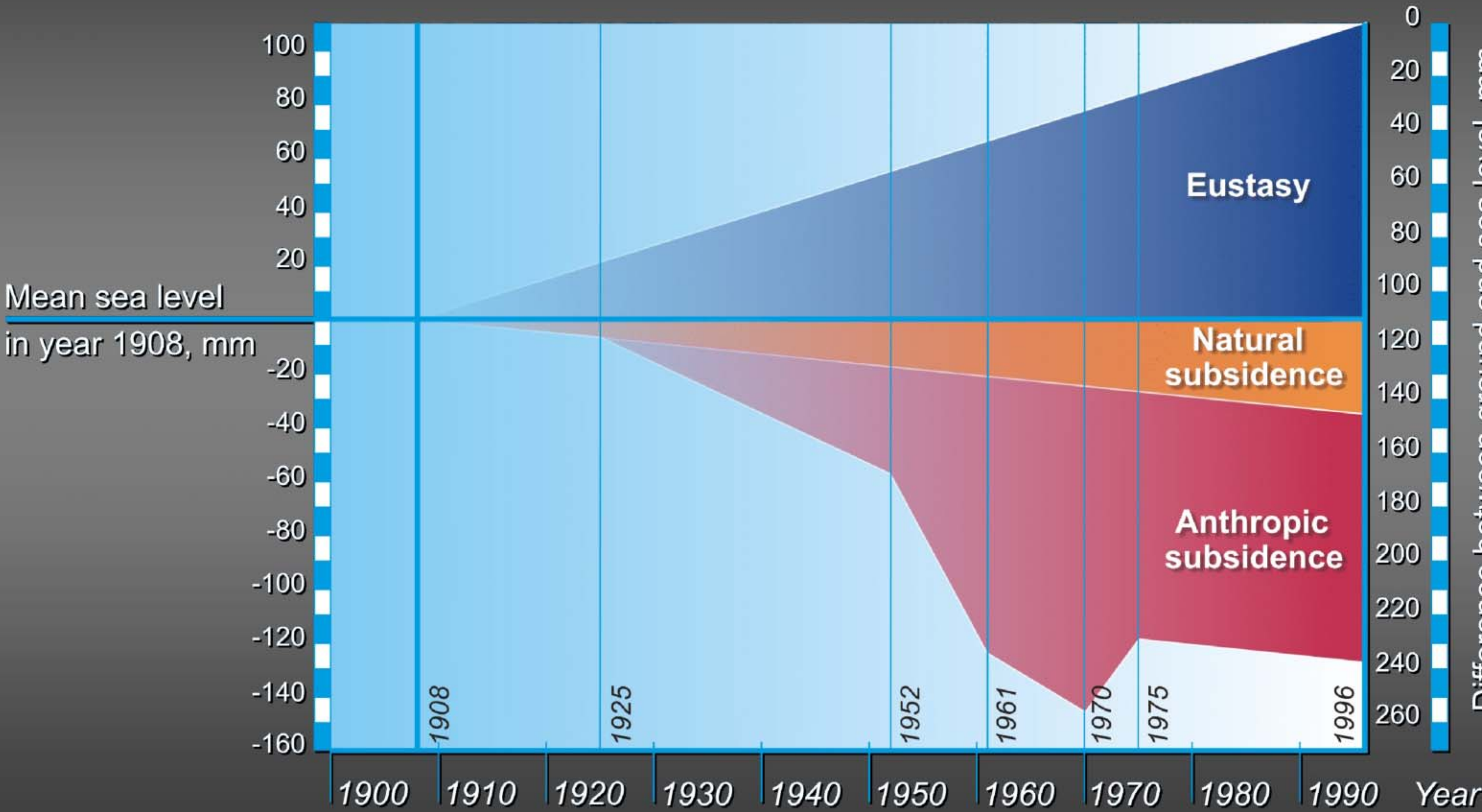
Water level exceeding +0.8m above msl., triggered by low atmospheric pressure combined with winds blowing from Adriatic sea and possible heavy rainfall

EXCEPTIONALLY HIGH TIDE:

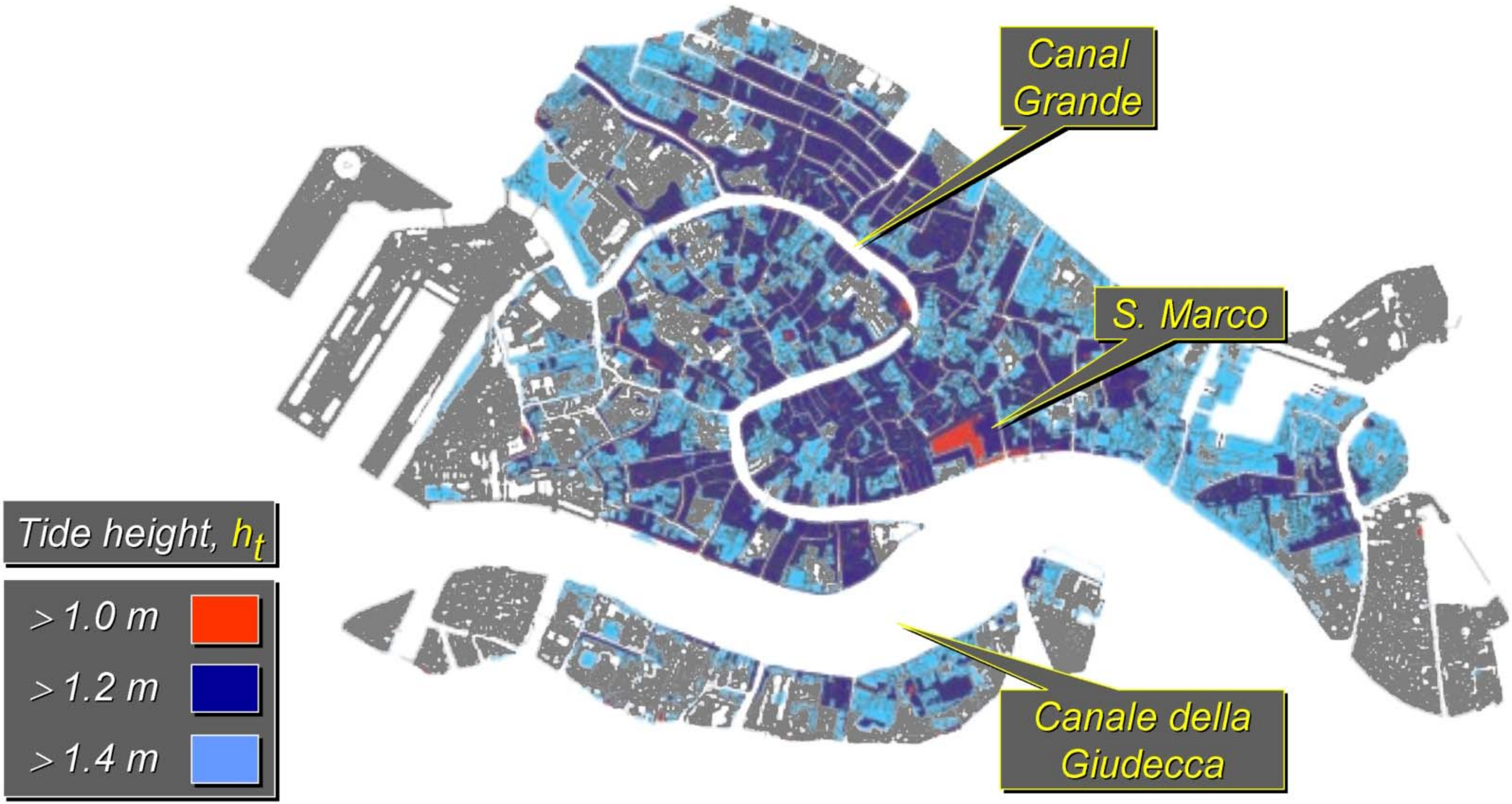
Water level exceeding 1.10m above msl.

▶ **MOBILE BARRIERS CLOSE LAGOON INLETS**

EUSTASY AND SUBSIDENCE OF VENICE FROM 1908



VENICE: AREAS FLOODED DURING HIGH TIDES



Lecture Outline

- Introductory remarks
- **Protection from high tides**
  - Historical background
  - **Selected solution**
- Lagoon subsoil
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INLETS TO VENICE LAGOON

SAFEGUARDING THE VENICE LAGOON AGAINST HIGH TIDES

ANTI-FLOOD BARRIERS AT THREE INLETS

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

LIDO INLETS

MALAMOCCO INLET

CHIOGGIA INLET

LIS-05

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THE MOSE SYSTEM: GENERAL FEATURES

- **MOBILE OSCILLATING BOUNCY FOLD AWAY FLAP GATES CLOSING THREE LAGOON INLETS**
  - LIDO: San Nicolò barrier, Treporti barrier
  - MALAMOCCO barrier
  - CHIOGGIA barrier
- **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

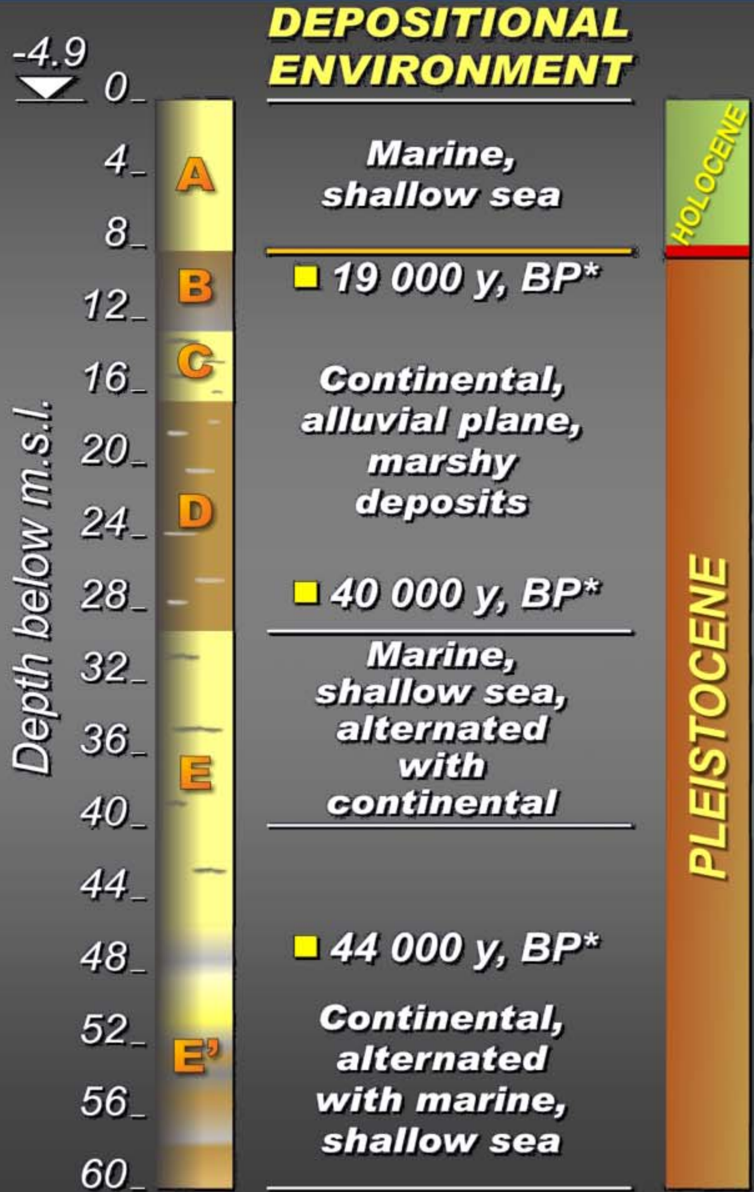
- Introductory remarks
- Protection from high tides
  - Historical background
  - Selected solution
- **Lagoon subsoil**
- Foundation problems
- Closing remarks

VENICE LAGOON – QUATERNARY DEPOSITS

- ***Sequence of alternating marine transgressions and regressions***
- ***Upper Pleistocene deposits 70 to 80 m thick covered by 8 to 15 m of Holocene deposits***
- ***Interbedded layers of sands, silts and odd silty clays***
- ***Pronounced spatial heterogeneity***

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
- (red bar) "Caranto" - end of Pleistocene deposition

(*) Radio Carbon C_{14}

SITE INVESTIGATION FOR FINAL DESIGN

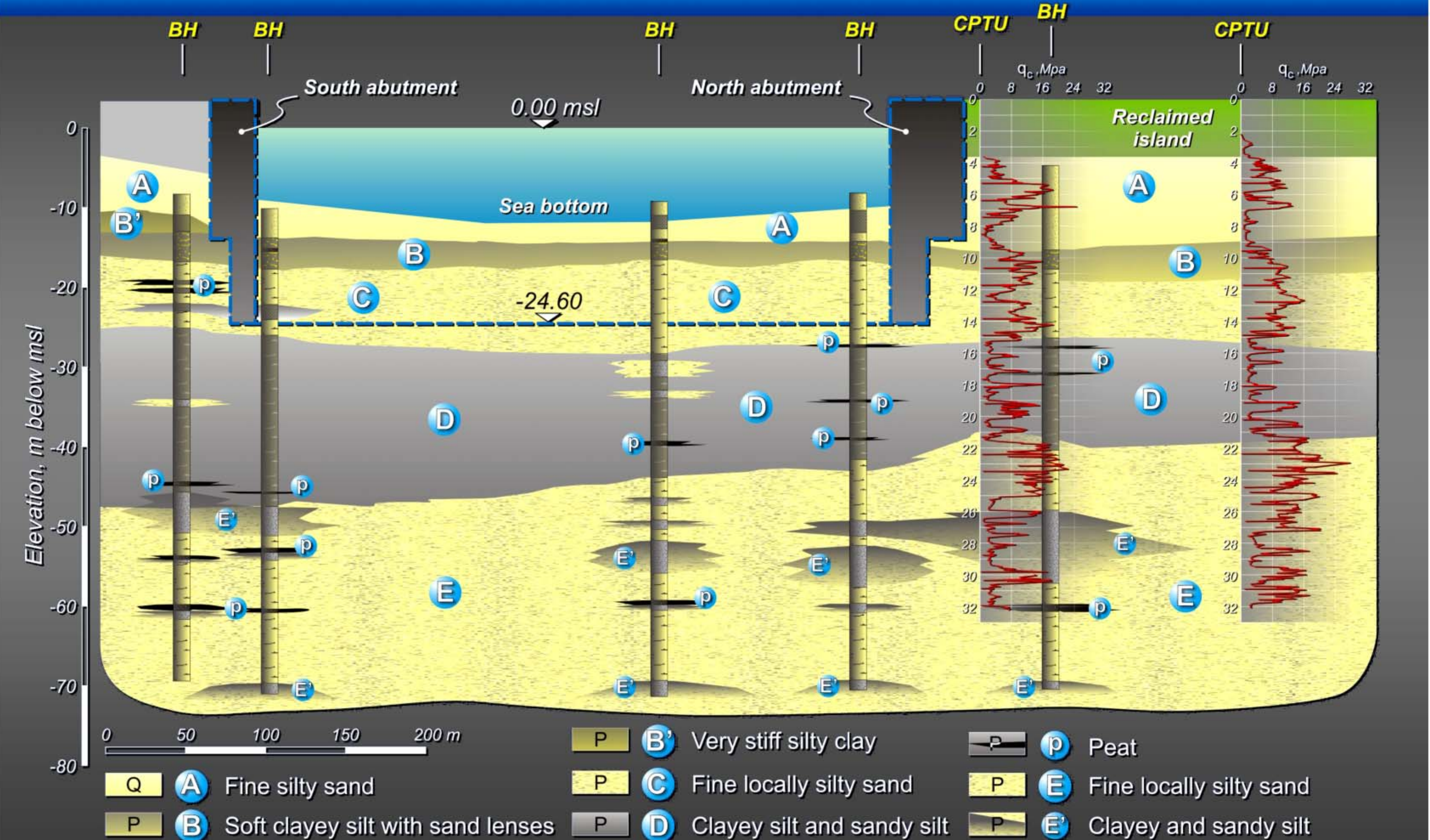
(2001 to 2004)

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

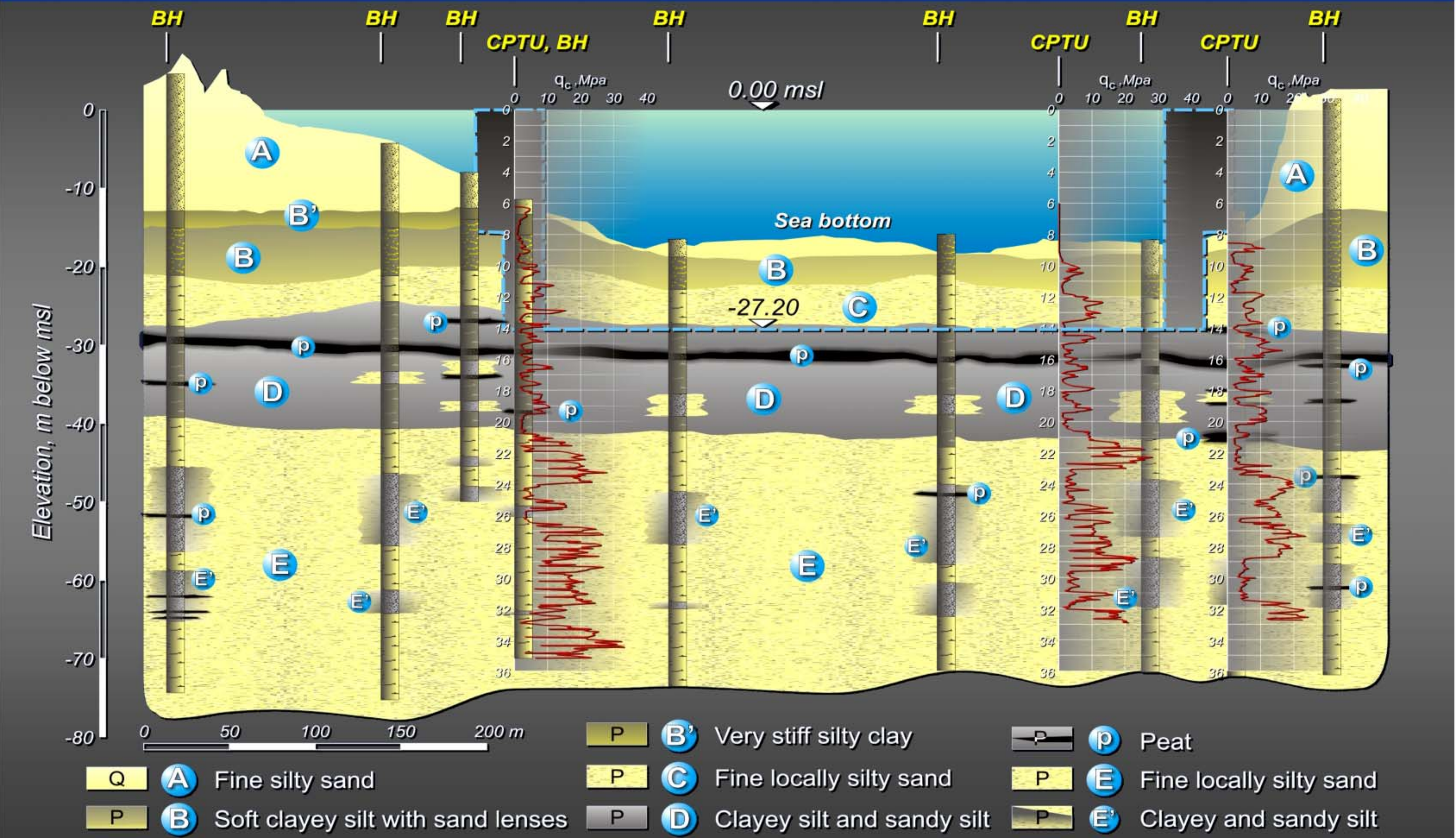
- **BH** ▶ Geotechnical borings; undisturbed sampling, **SPT**'s, **FVT**'s
- **CPTU** ▶ Static Cone Penetration Test with pore pressure measurement
- **DMT** ▶ Marchetti's Flat Dilatometer Test
- **SPT-BH** ▶ Standard Penetration Test, carried out in dedicated 3" O.D. holes

- 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 %

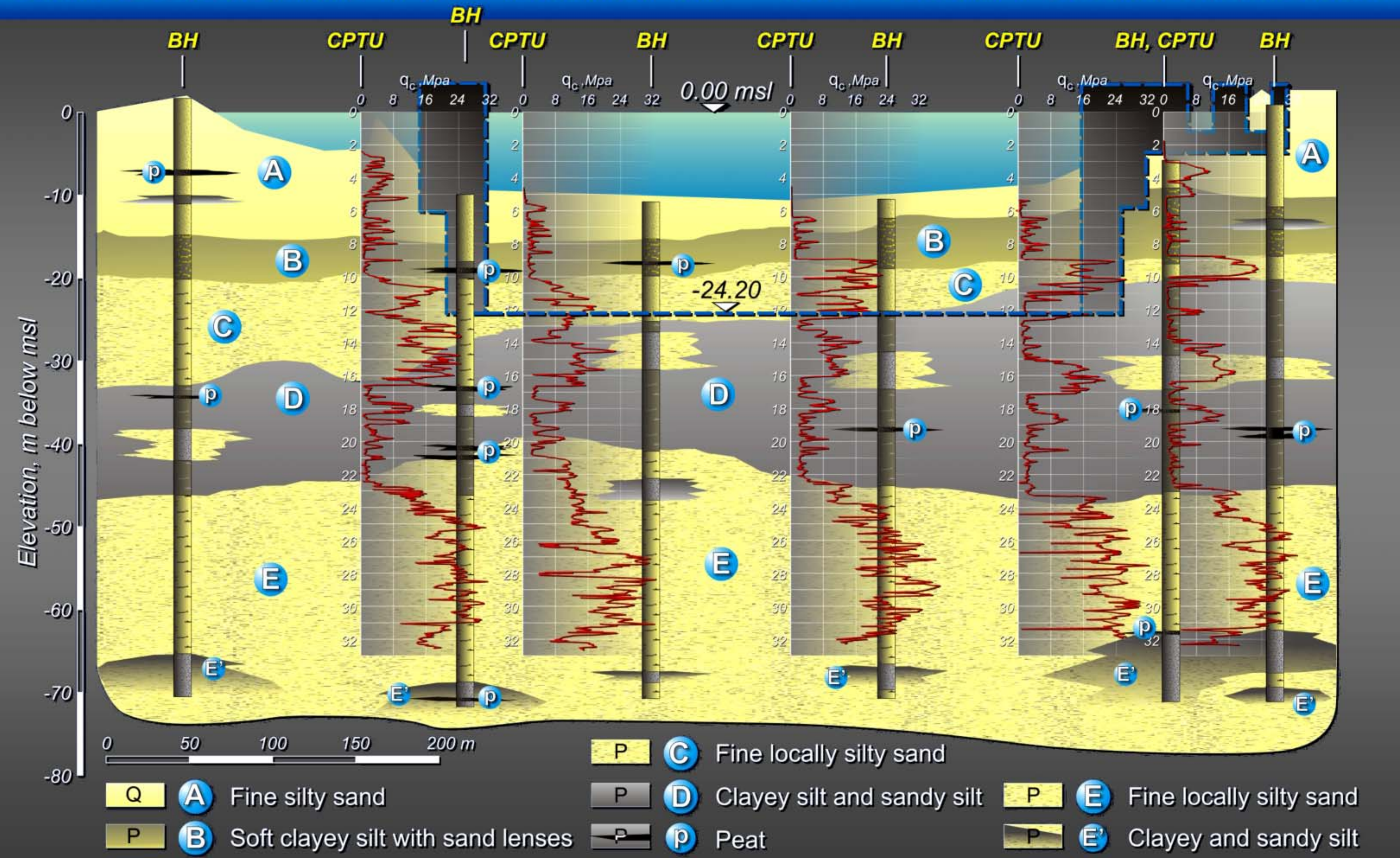
LIDO INLET – SAN NICOLO' BARRIER – SUBSOIL CONDITIONS



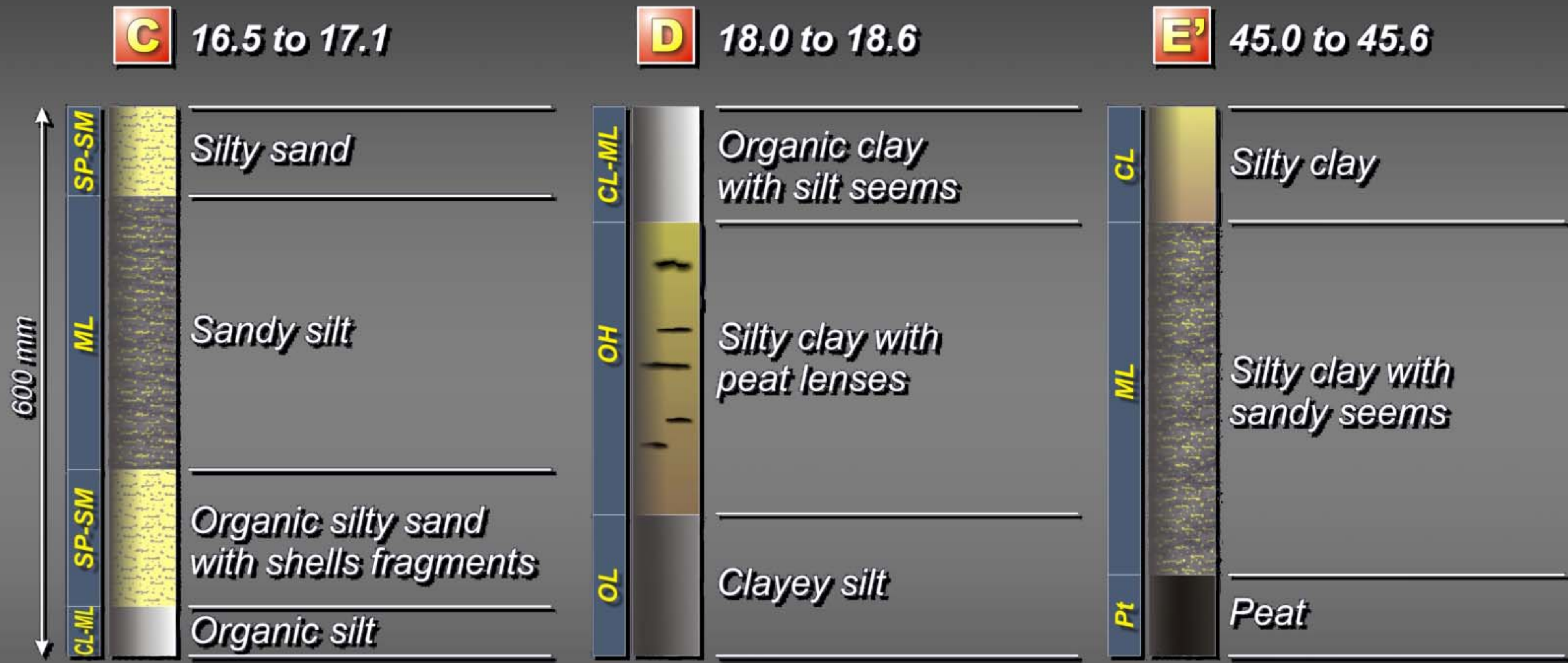
MALAMOCCO BARRIER – SUBSOIL CONDITIONS



CHIOGGIA INLET BARRIER – SUBSOIL CONDITIONS

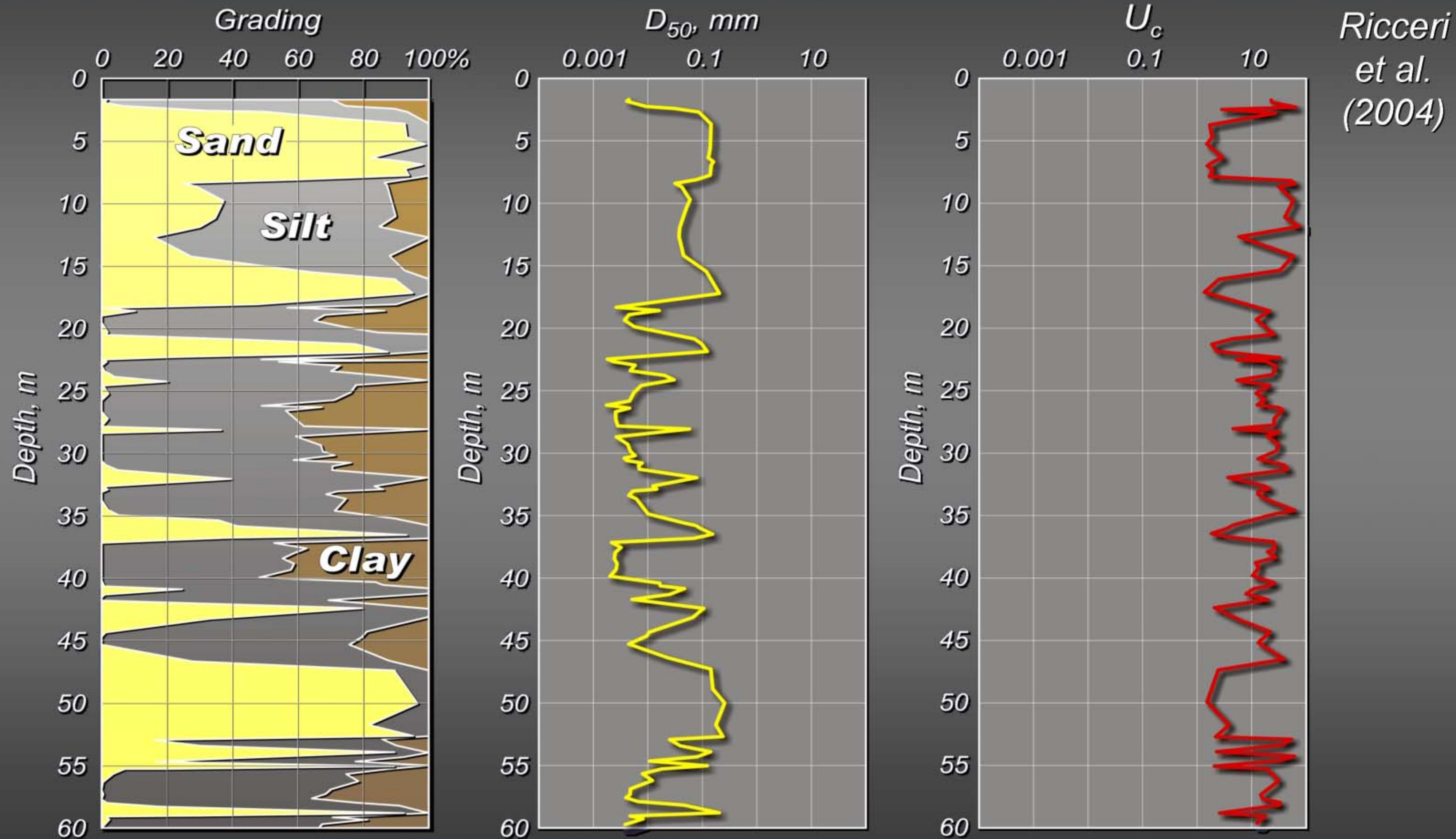


LAGOON DEPOSITS
EXAMPLES OF HETEROGENEITY AT SMALL SCALE

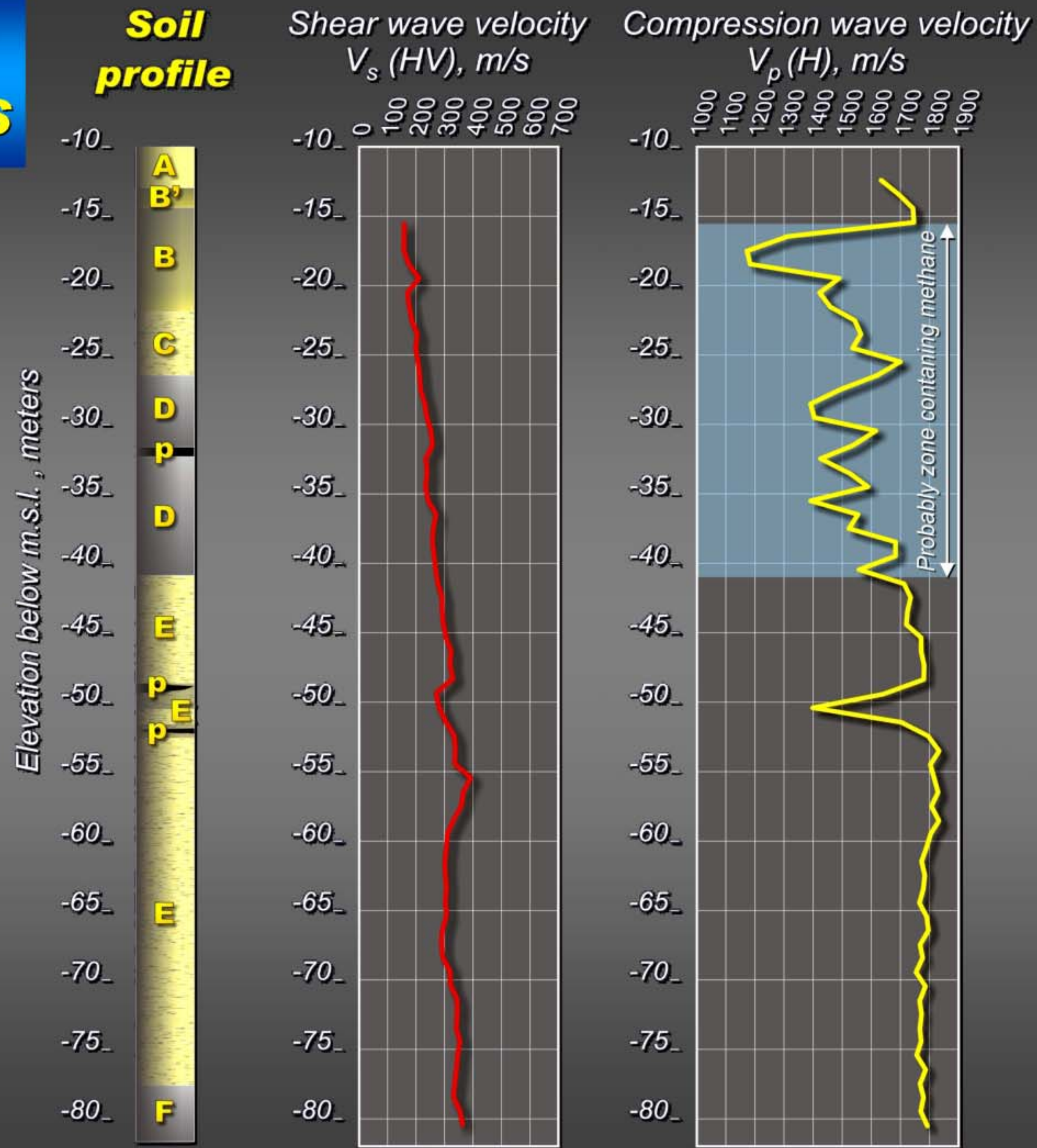


PRONOUNCED VARIABILITY OF INDEX AND MECHANICAL SOIL PROPERTIES IN BOTH VERTICAL AND HORIZONTAL DIRECTION

LIDO TRIAL EMBANKMENT
SOIL GRADING VARIATION WITH DEPTH

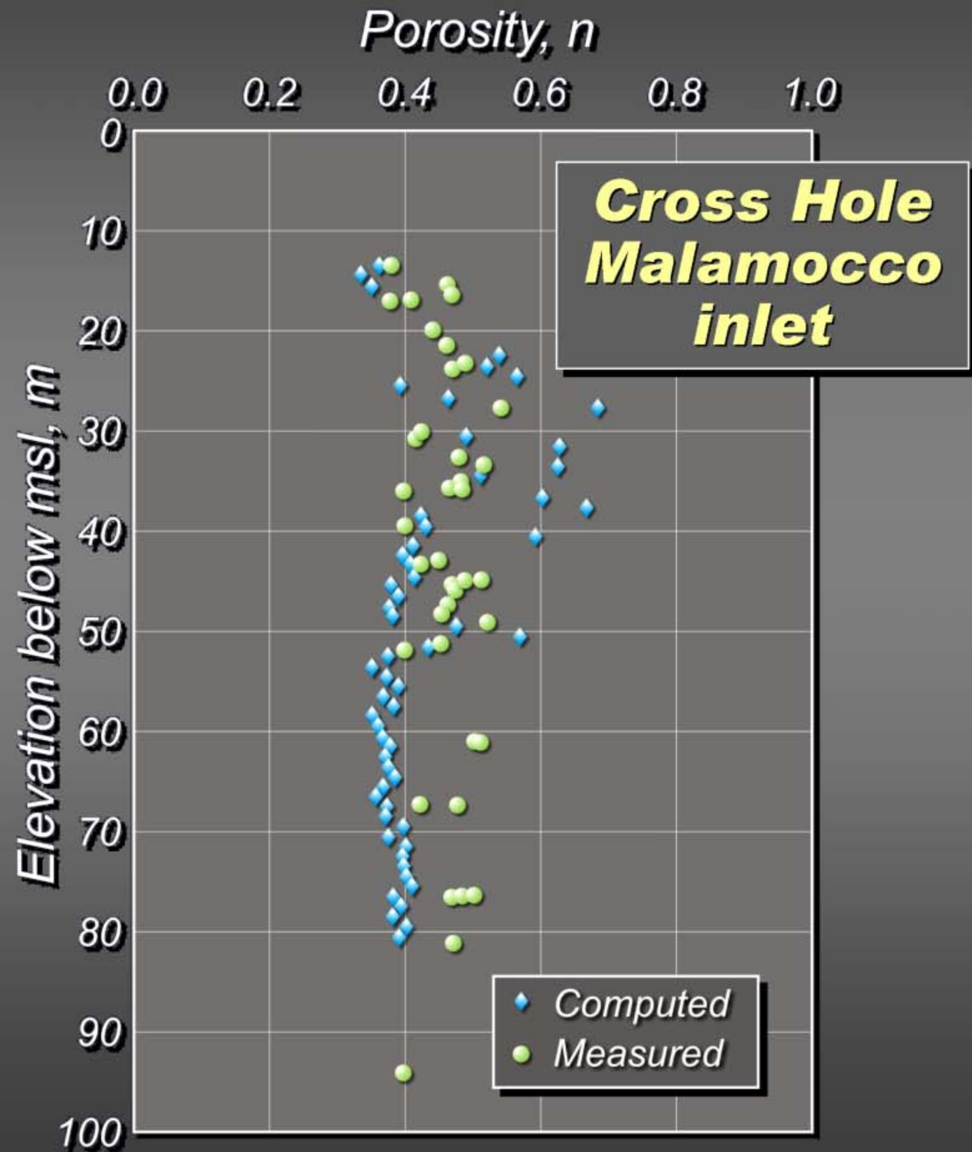


MALAMOCCO INLET
CROSS-HOLE TEST RESULTS



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

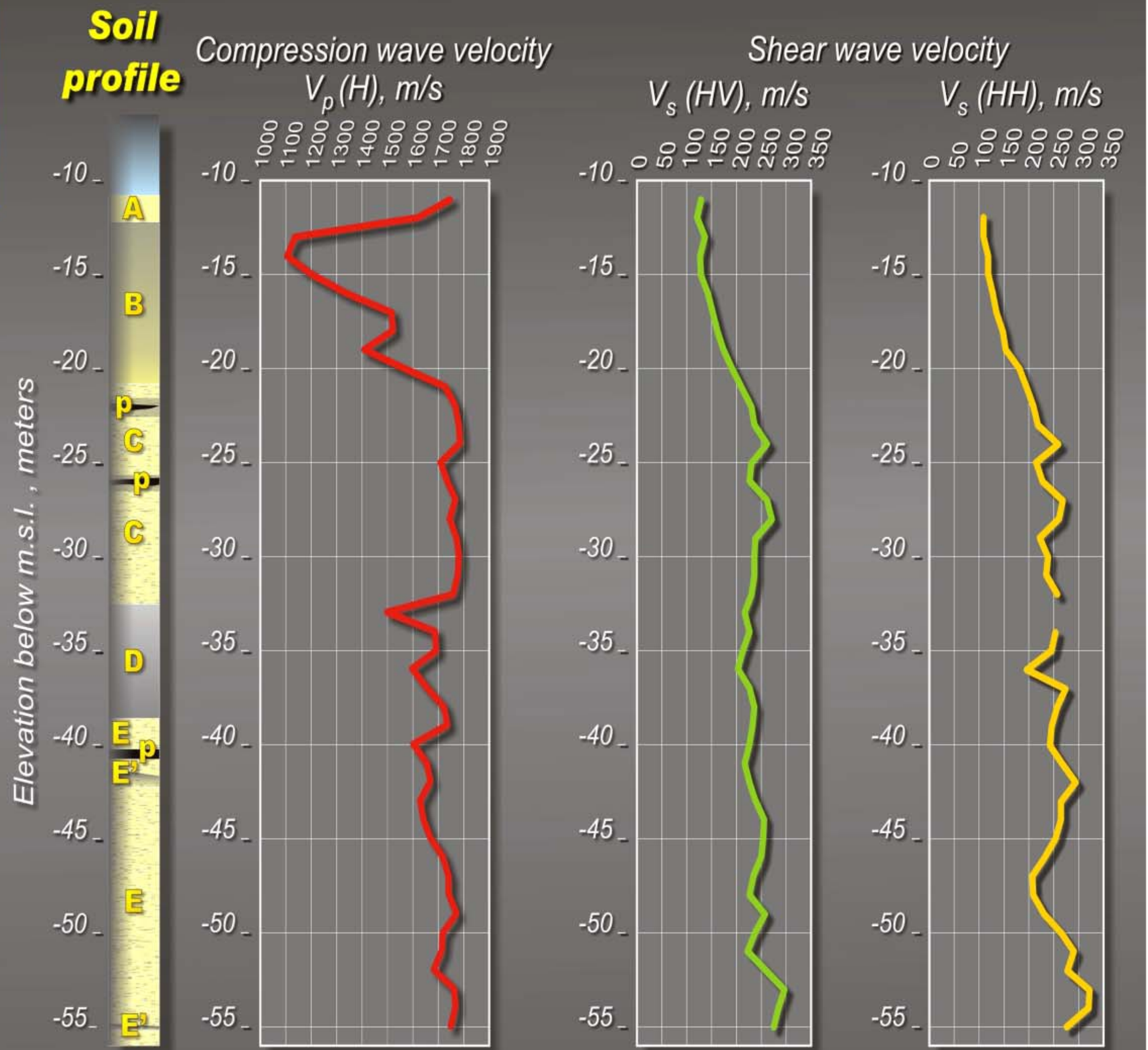
ρ_s = soil particles } mass density

ρ_f = pore fluid } mass density

K_f = bulk modulus of pore fluid

ν_s = Poisson ratio of soil skeleton

CHIOGGIA INLET CROSS-HOLE TEST RESULTS



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CHIOGGIA INLET
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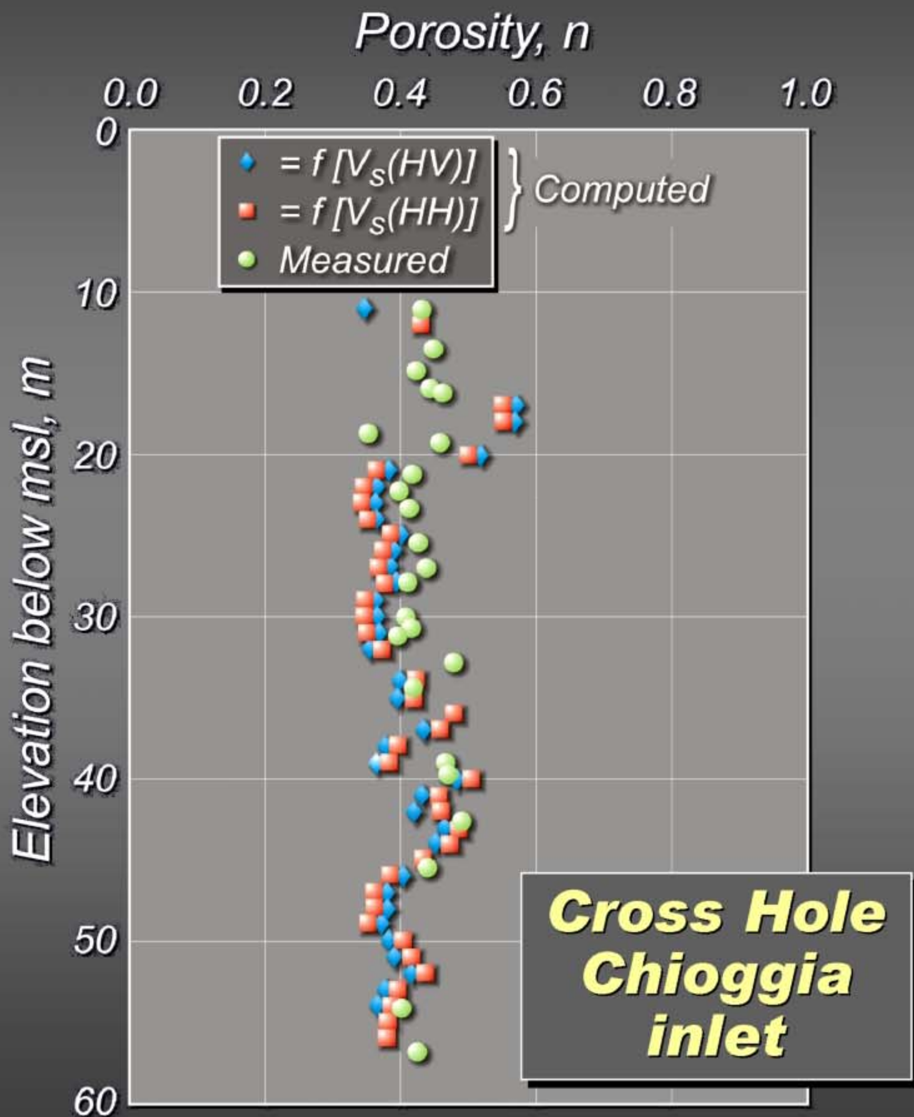

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Connected porosity

ρ_s = soil particles } mass density

ρ_f = pore fluid } mass density

K_f = bulk modulus of pore fluid

ν_s = Poisson ratio of soil skeleton

IMPACT OF SPATIAL DEPOSITS HETEROGENEITY ON SITE CHARACTERIZATION

- Geotechnical design profile difficult to establish
- Drainage and boundary conditions uncertainties hamper in situ tests interpretation
- Difficulties to single out design parameters from laboratory test results
- Limitations in using advanced constitutive models in numerical analyses

VENETIAN LAGOON: LOCATION OF TRIAL EMBANKMENT

Treporti
Experimental Site:
Trial Embankment

TRIAL EMBANKMENT

During construction

Reinforced earth wall

Completed

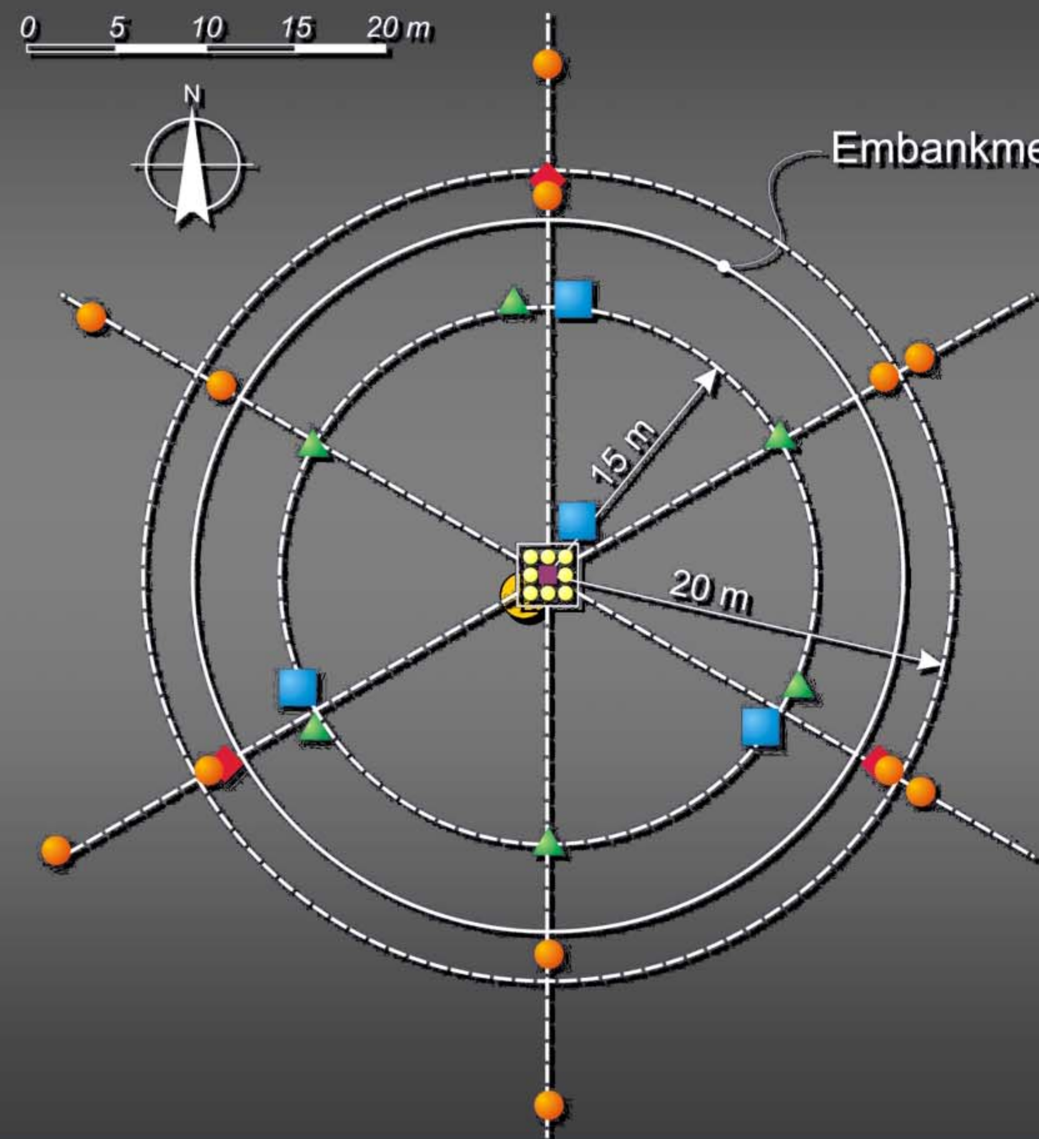
TRIAL EMBANKMENT: MONITORING INSTRUMENTATION

Ricceri et al. (2004)

Instruments location

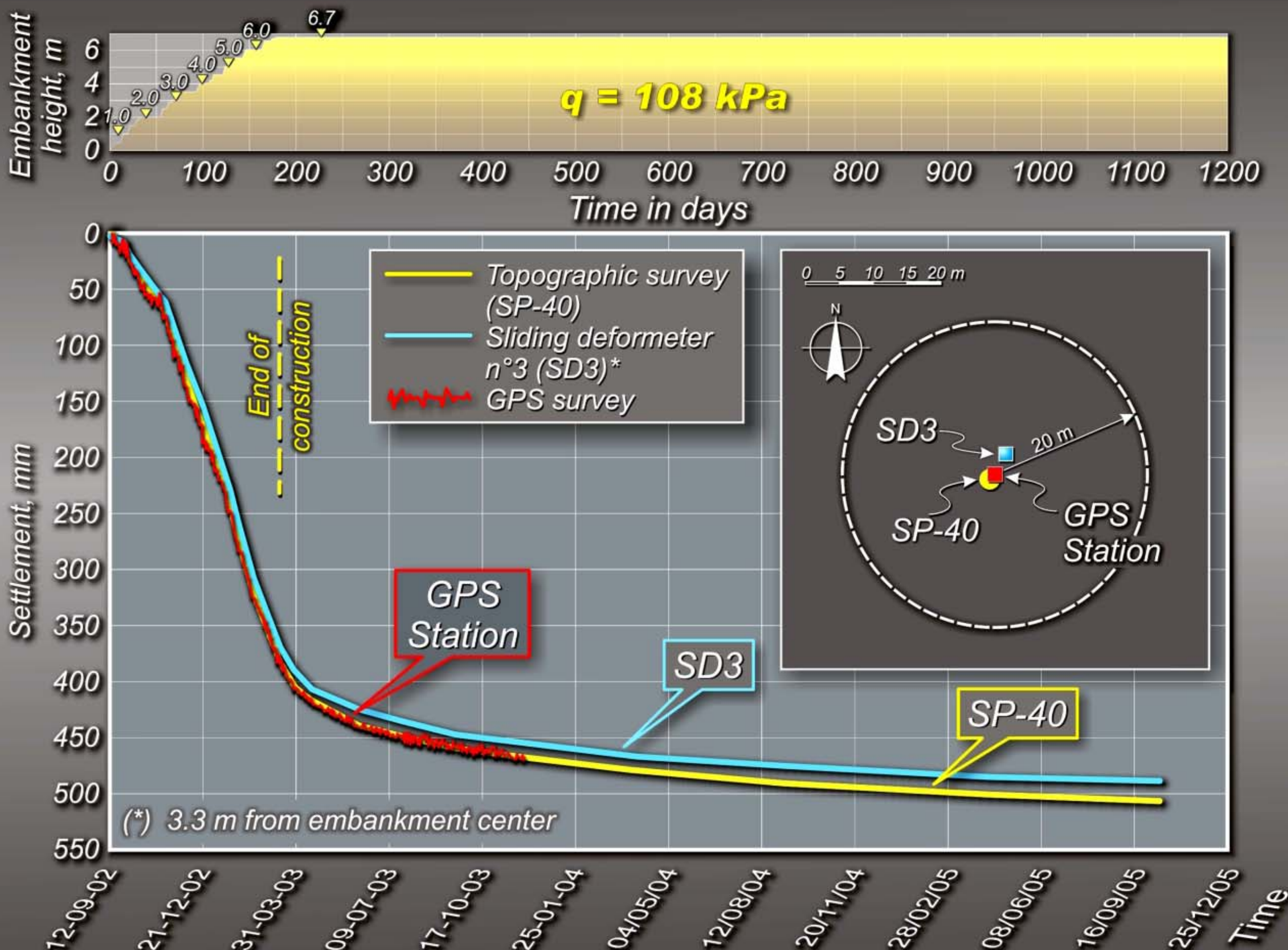
- GPS station
- Deep settlement plates
- Sliding deformeters
- Inclinometers
- Benchmarks
- Surface settlement plates
- Topographic survey

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

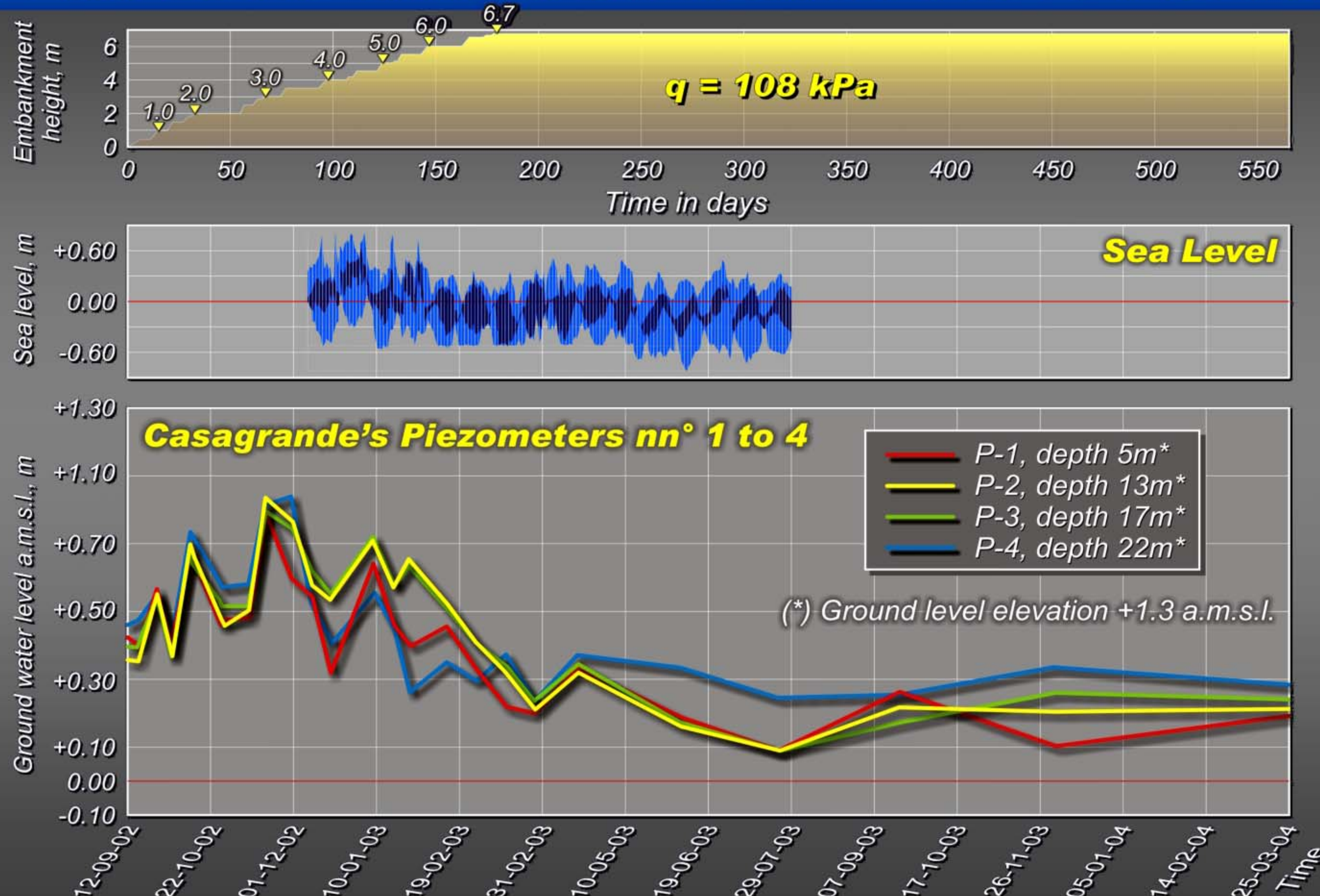


CENTER OF TRIAL EMBANKMENT: TIME-SETTLEMENT CURVE

Ricceri et al. (2004)



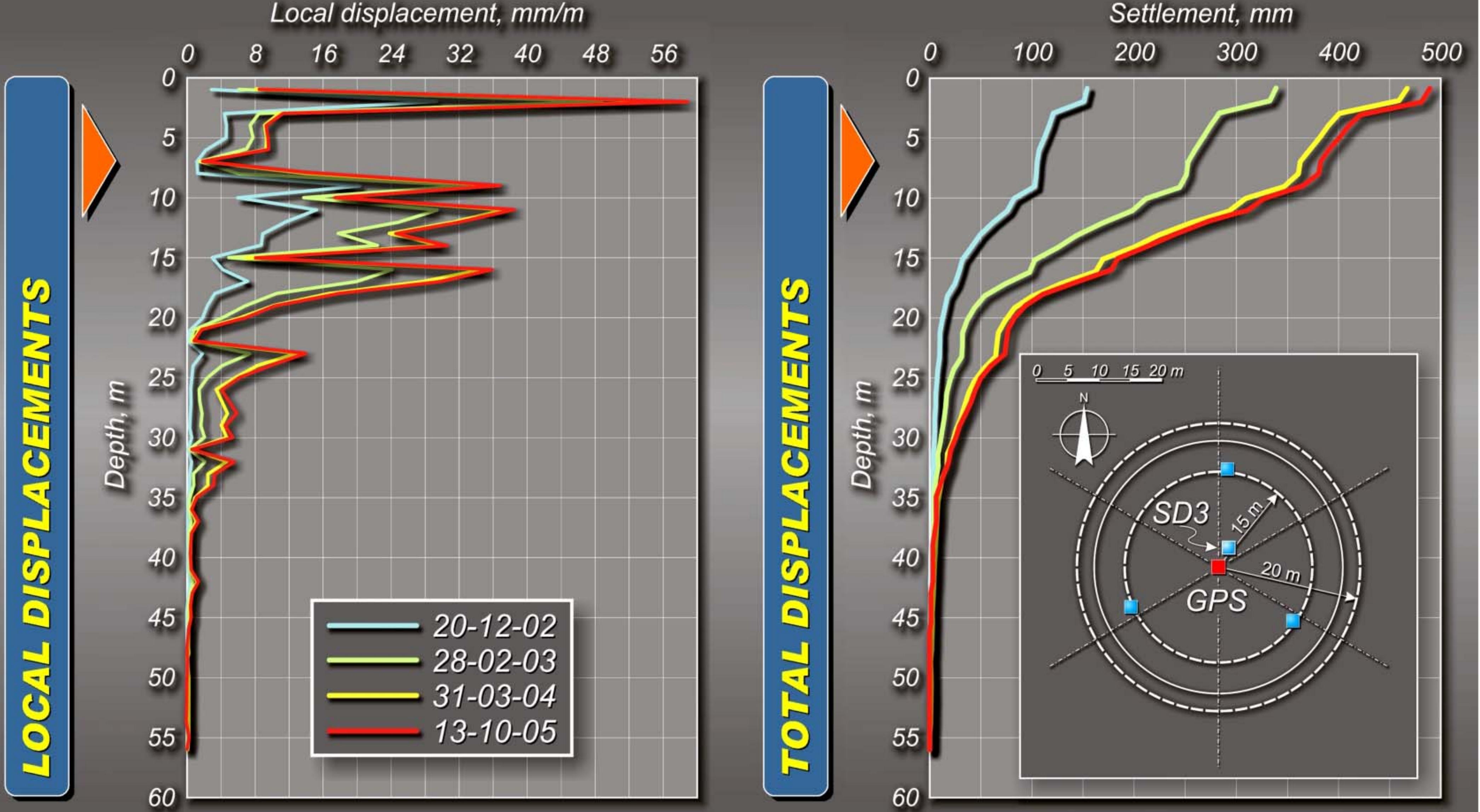
TRIAL EMBANKMENT: PORE PRESSURE FROM CASAGRANDE's PIEZOMETERS



Ricceri et al. (2004)

TRIAL EMBANKMENT: VERTICAL DISPLACEMENTS

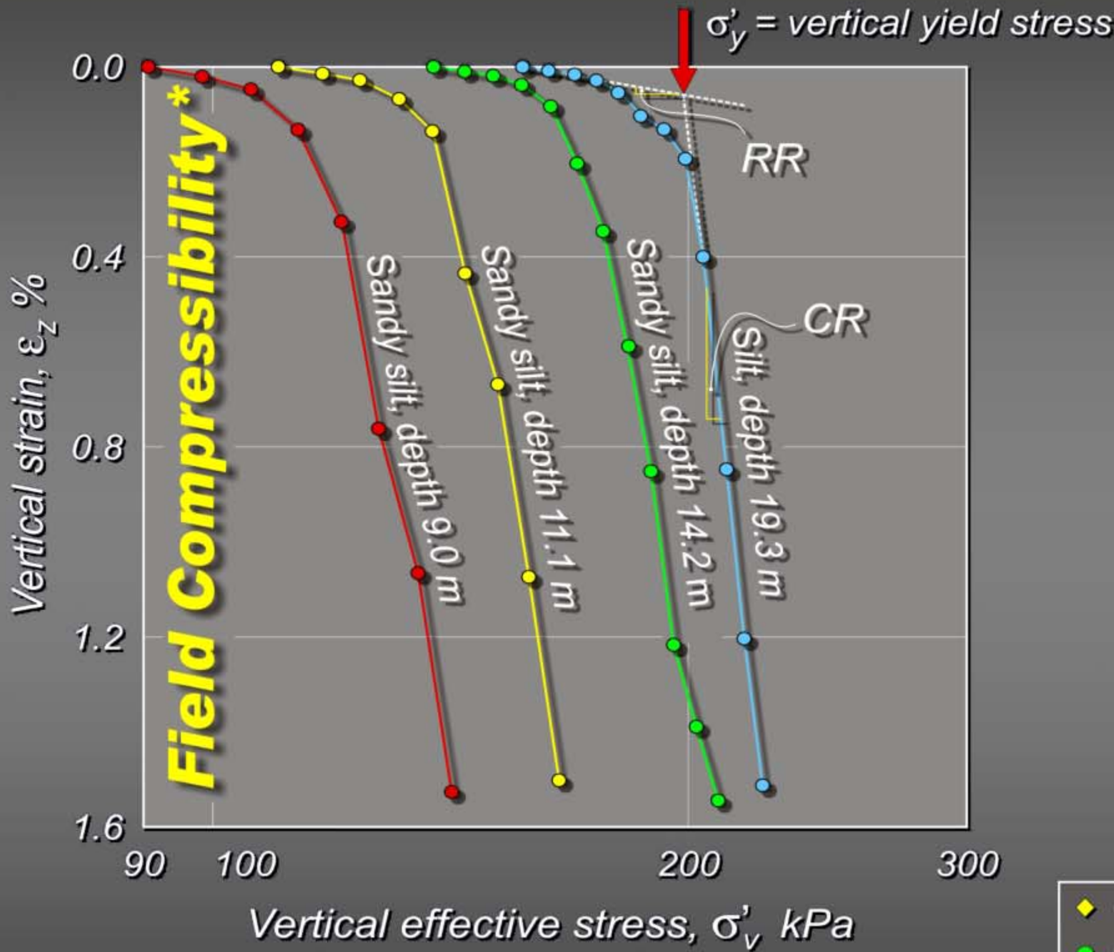
Sliding Deformeter n°3 – Ricceri et al. (2004)



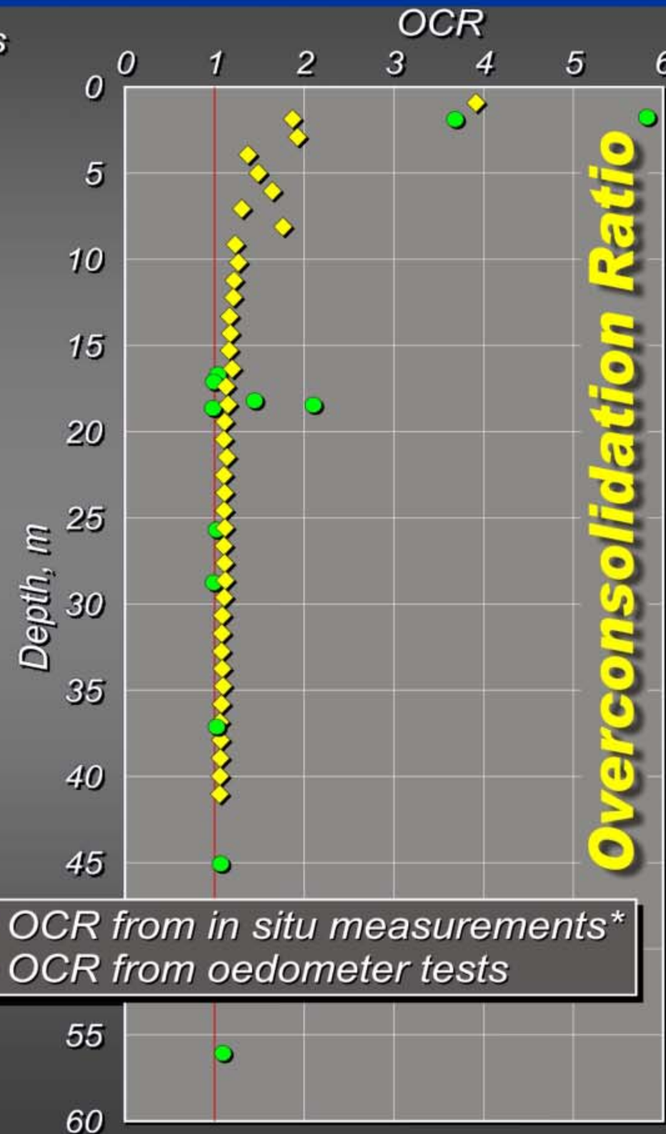
LIDO INLET - TRIAL EMBANKMENT

Subsoil stress history

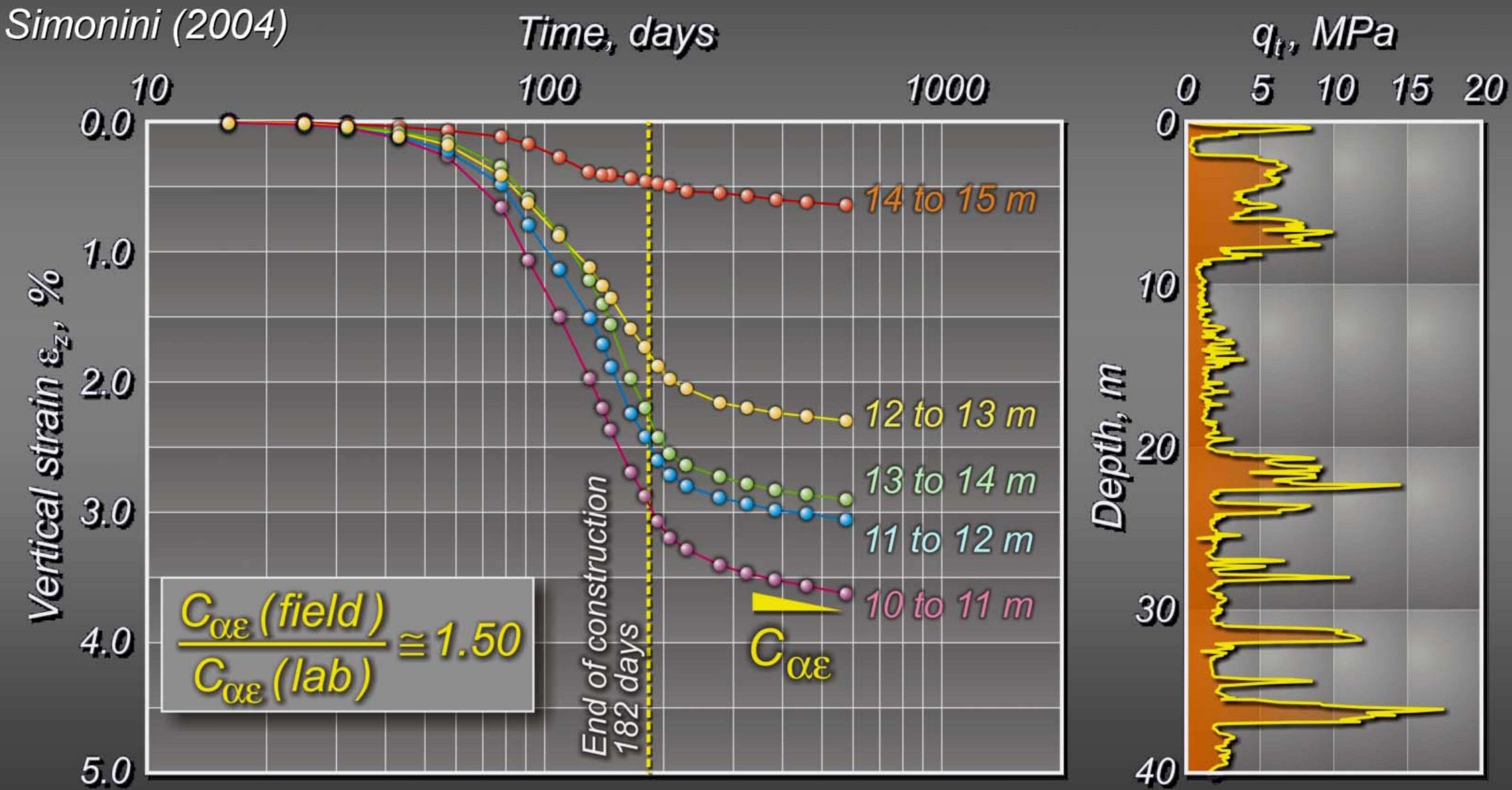
Ricceri et al. (2004)



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



VENICE LAGOON DEPOSITS
COEFFICIENT OF SECONDARY COMPRESSION IN SITU
(Sliding deformeter readings)



RECOMPRESSION RATIO and SECONDARY COMPRESSION COEFFICIENT IN SITU vs. LABORATORY

SOIL TYPE*	$\frac{RR\ (lab)}{RR\ (in\ situ)}$	$\frac{C_{\alpha\varepsilon}\ (in\ situ)}{C_{\alpha\varepsilon}\ (lab)}$
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

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ANTI-FLOOD BARRIERS AT THREE INLETS

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

LIDO INLETS

MALAMOCCO INLET

CHIOGGIA INLET

LIS-05

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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

BARRIERS' FOUNDATIONS

Gentilomo (1997); Simonini (2004)

PREFABRICATED CONCRETE CAISSONS:

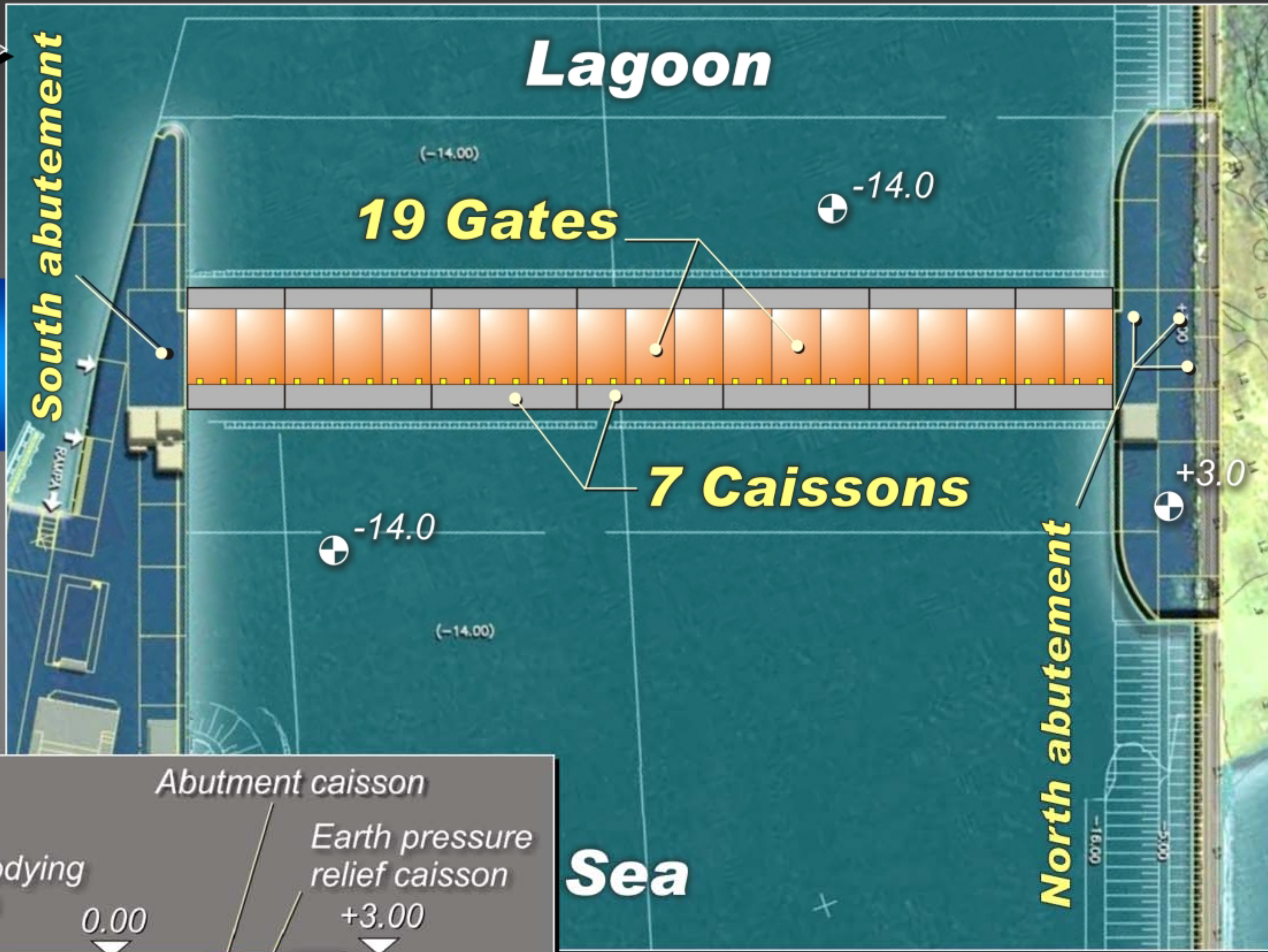
Height:	10 to 12 m
Width:	30 to 50 m
Length:	40 to 60 m

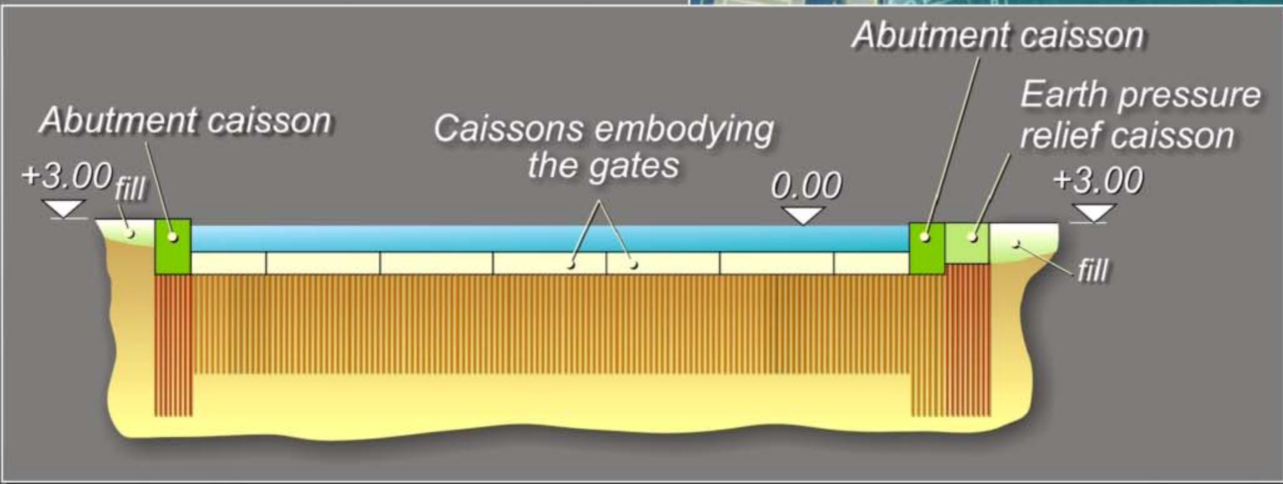
EACH CAISSON INCORPORATES:

- 2 to 3 flap gates
- Tunnels housing equipment controlling gates operation

MALAMOCCO BARRIER

Plan view



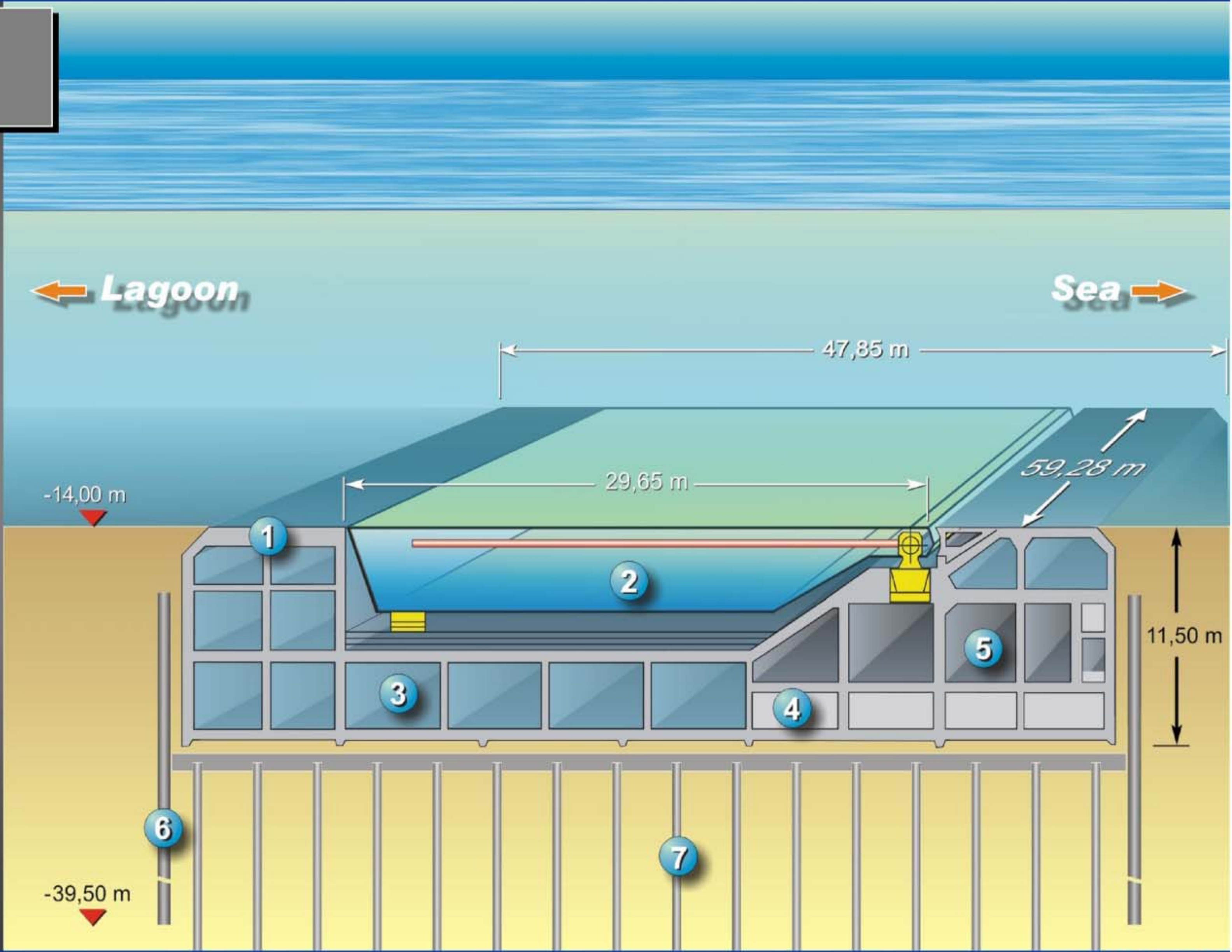


Schematic cross-section

FLOODGATES OPERATIONAL SCHEME

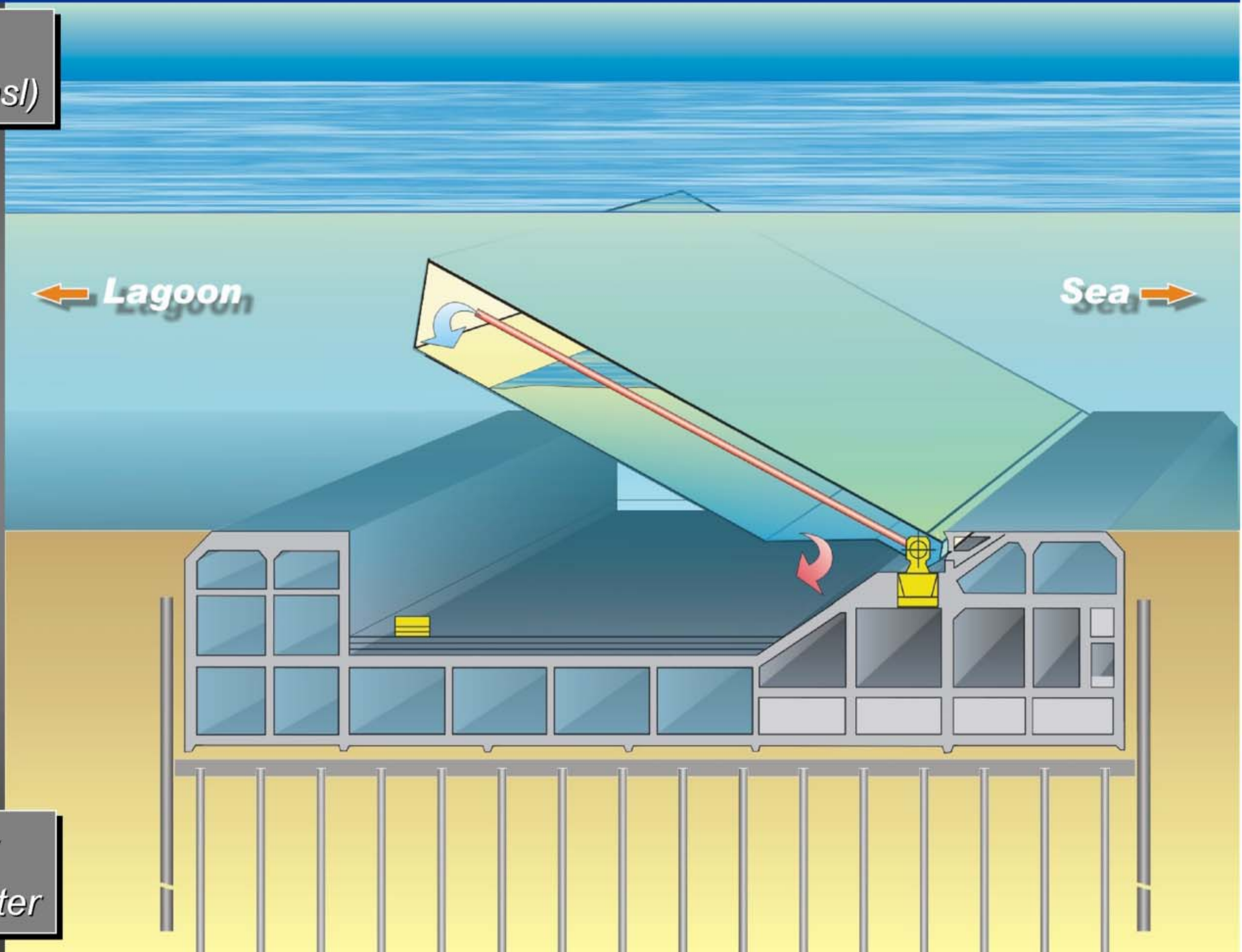
Gate quiescent
(inlet open)

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



FLOODGATES OPERATIONAL SCHEME

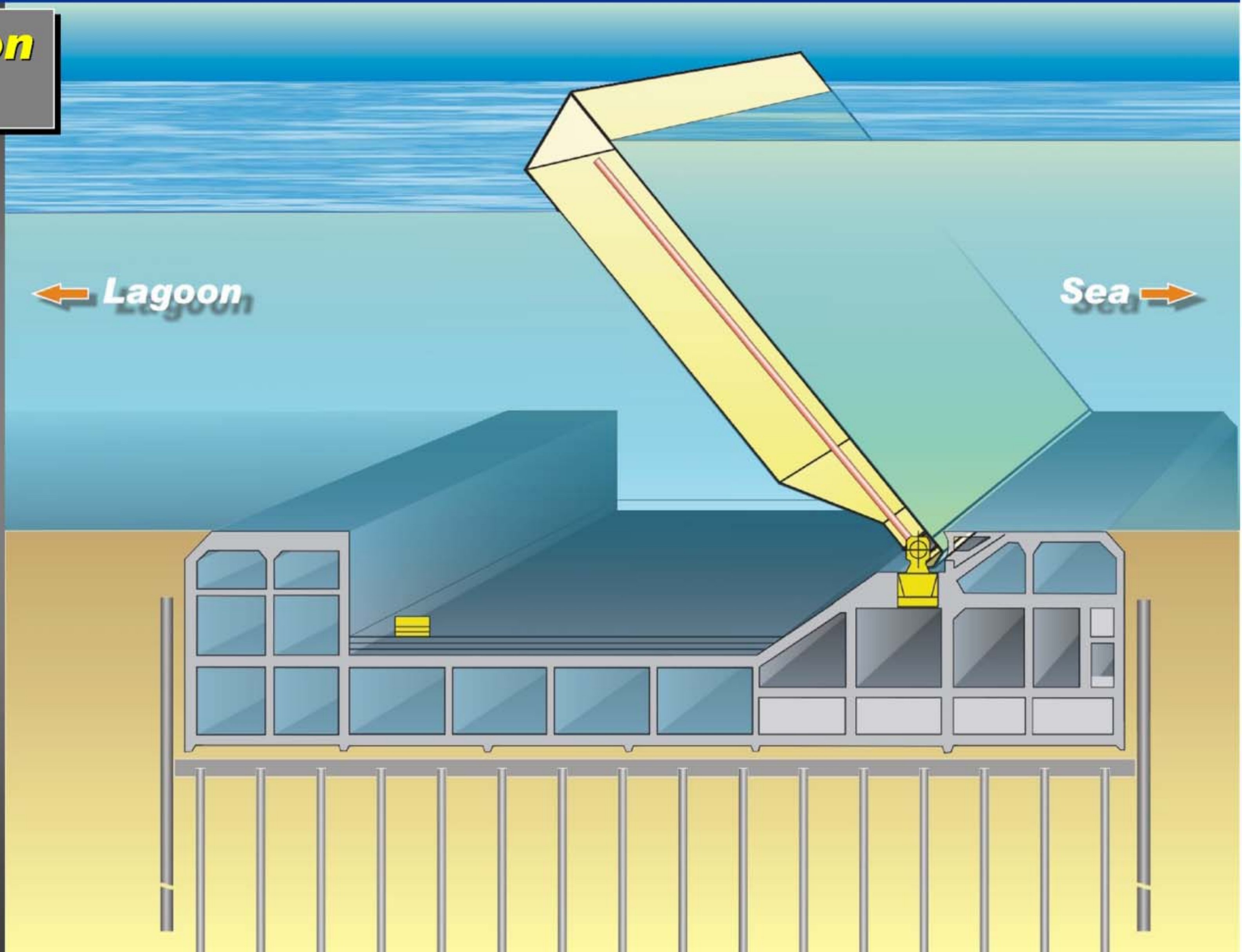
Gate raises
(tide level ≥ 1.10 m a. msl)



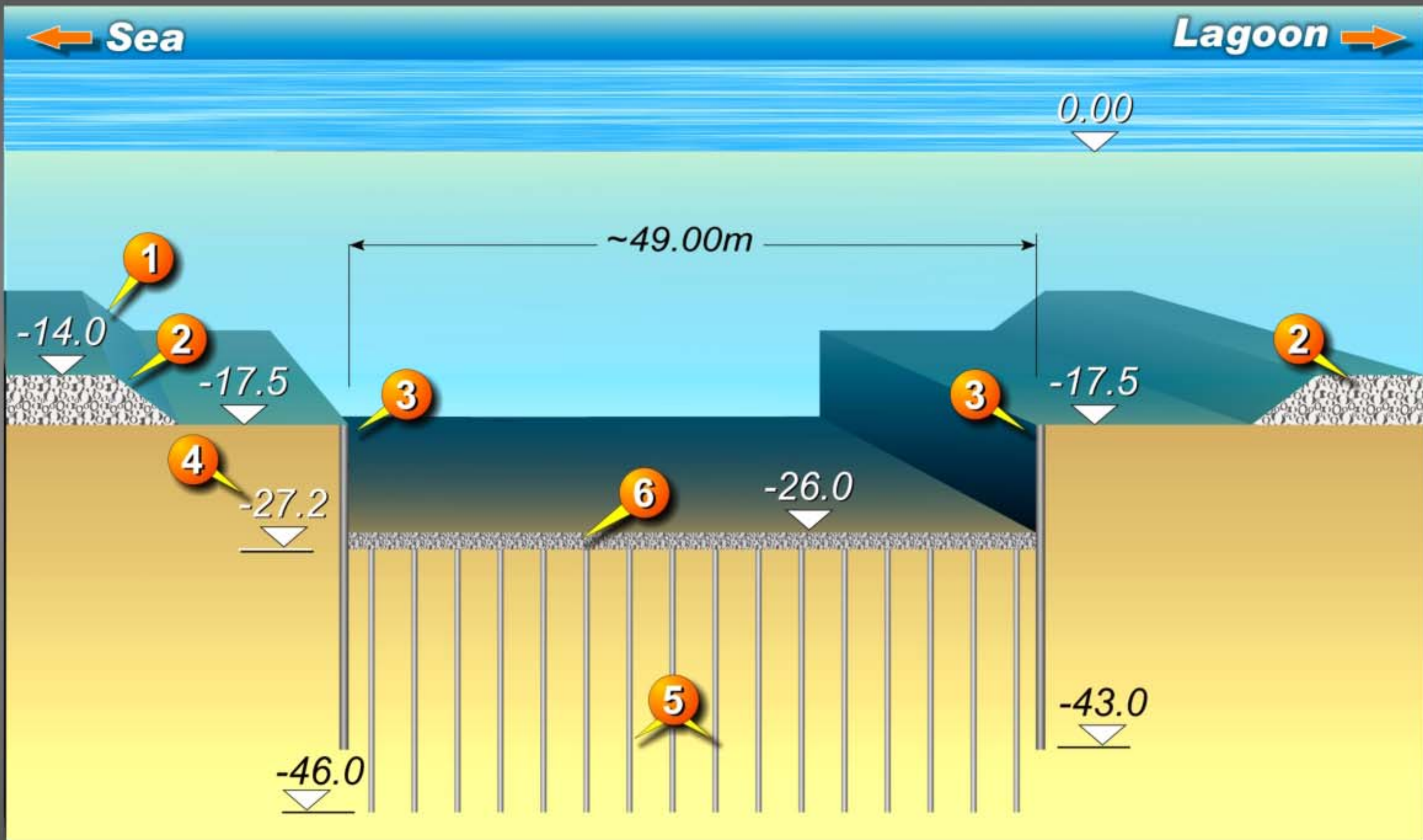
Immission of air
Expulsion of water

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

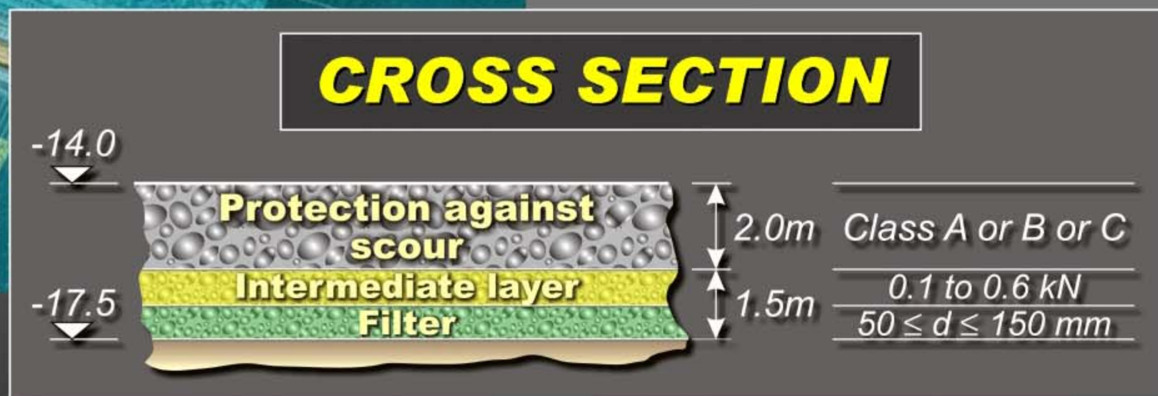
10 Caisson's balasting

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



Caissons embodying the mobile gates

Tolerable differential movements

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

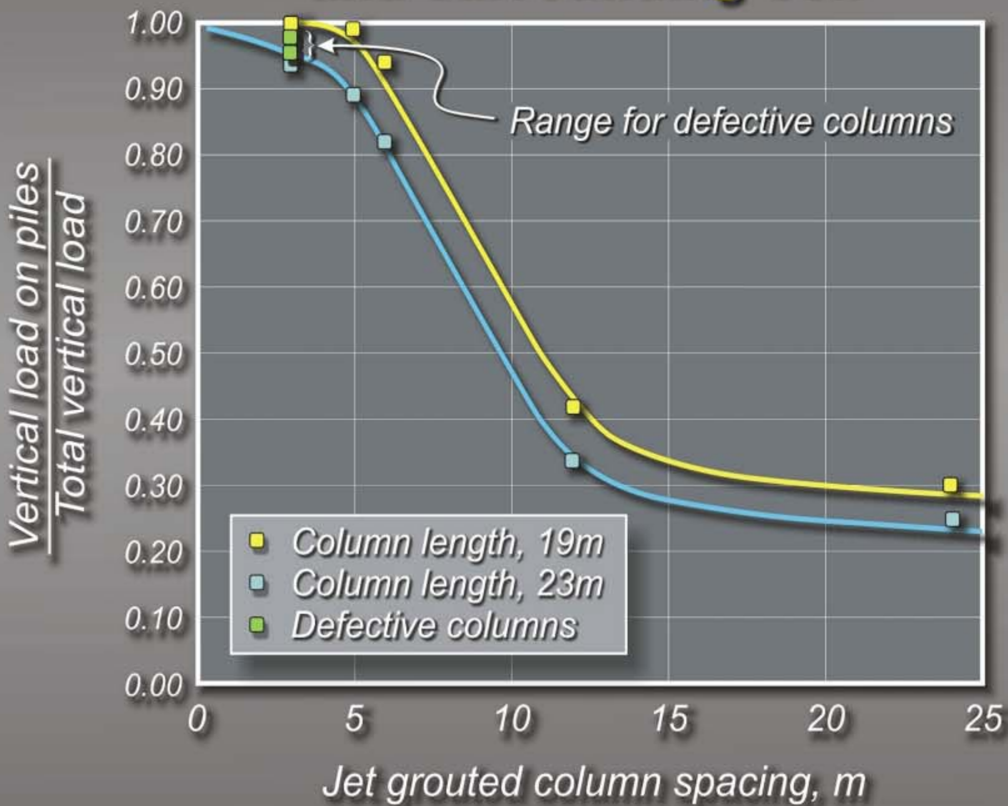
- **Most important: horizontal distance between two adjacent gates****

(*) Rubber joint of large dimensions, allowable value 40mm

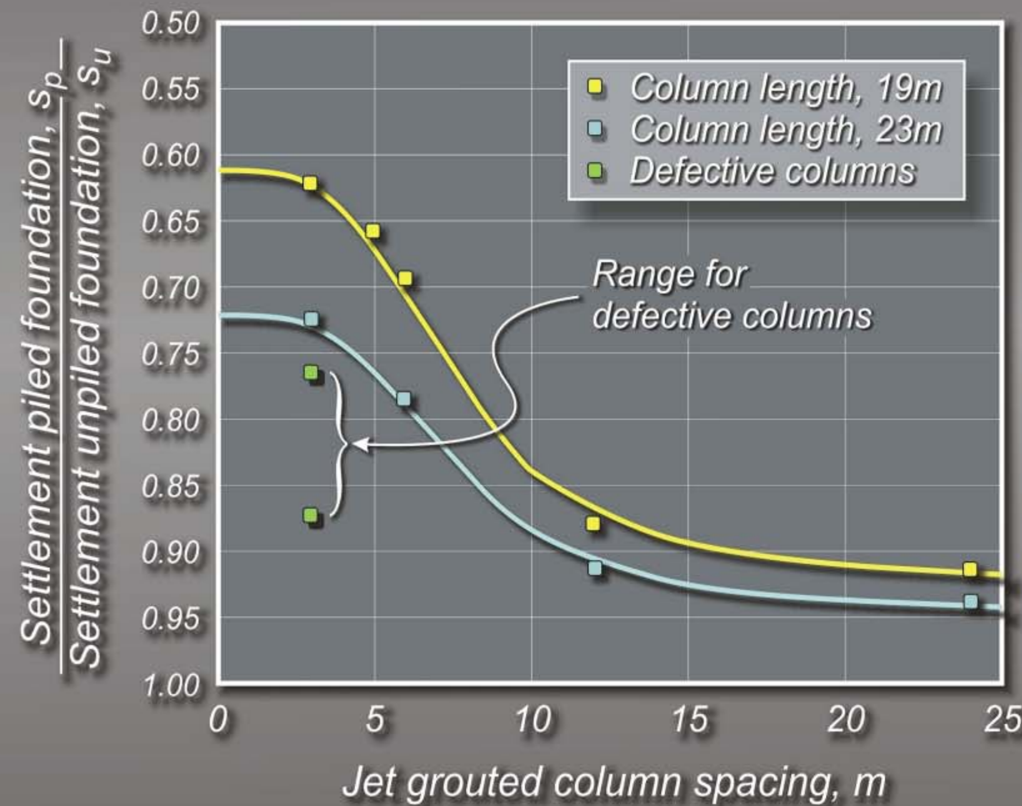
(**) Design value, 150 to 200mm

TREPORTI CAISSONS' FOUNDATIONS ON JET-GROUTED COLUMNS

Load sharing between piles and surrounding soil



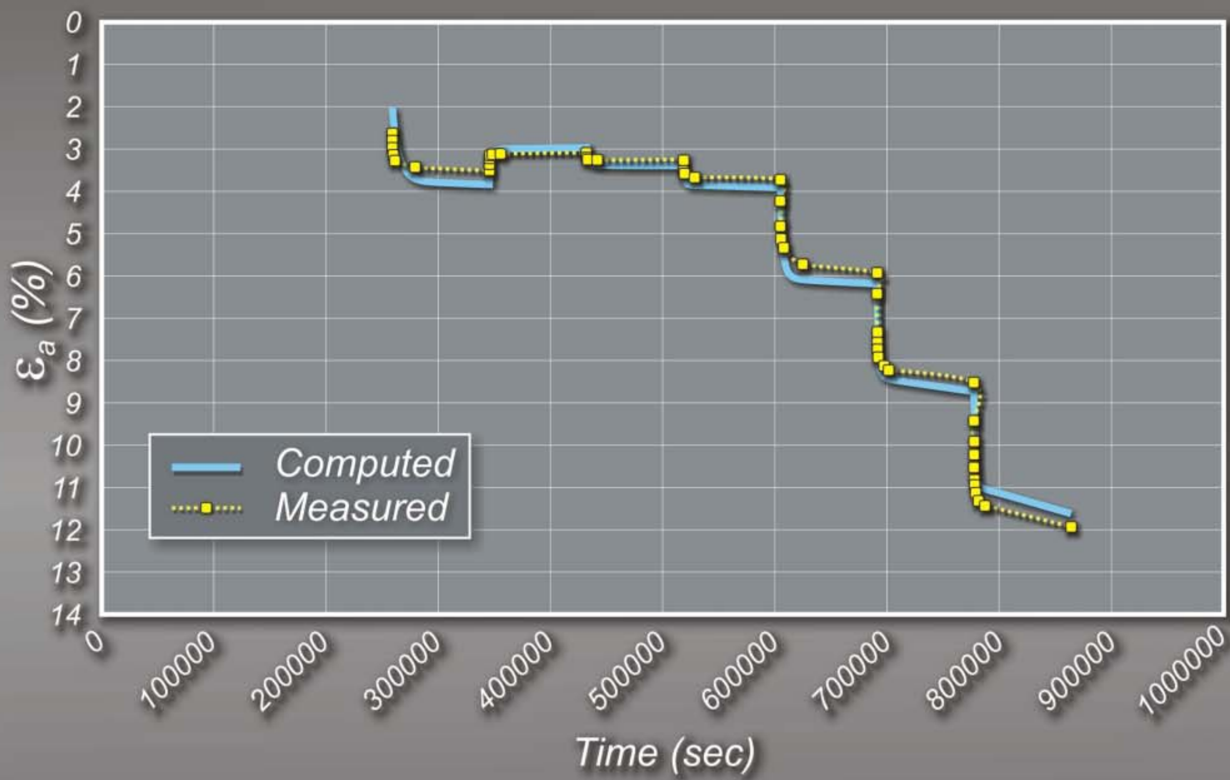
Settlement reduction factor

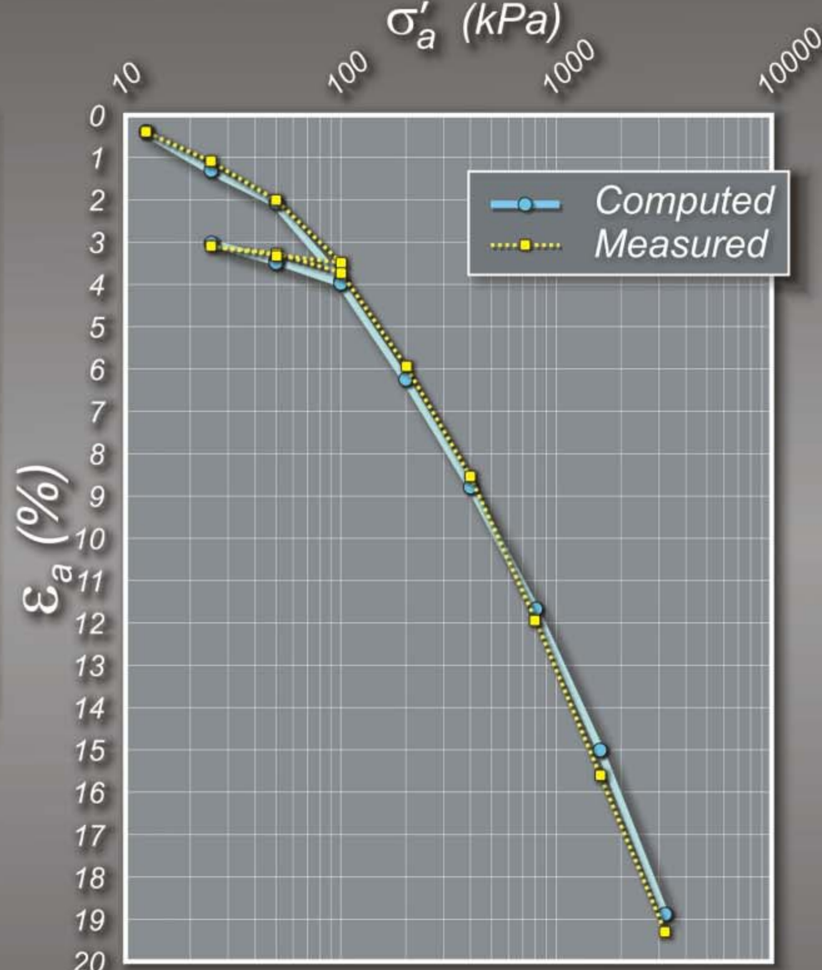


TREPORTI TRIAL EMBANKMENT
NUMERICAL SIMULATION* OF AN OEDOMETER TESTS

Layer B, Soft clayey silt

Time vs. strain curve

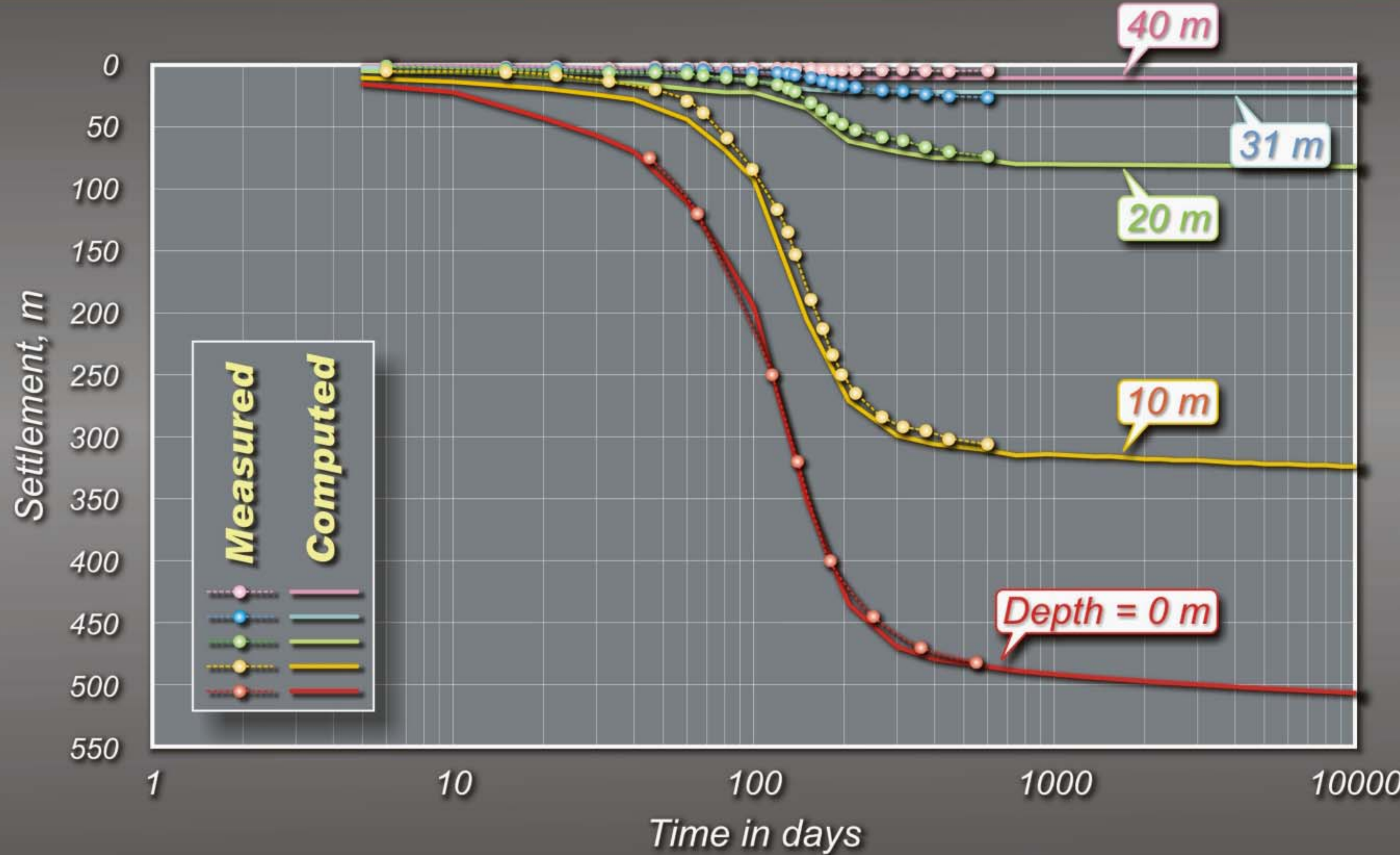




Stress vs. strain curve

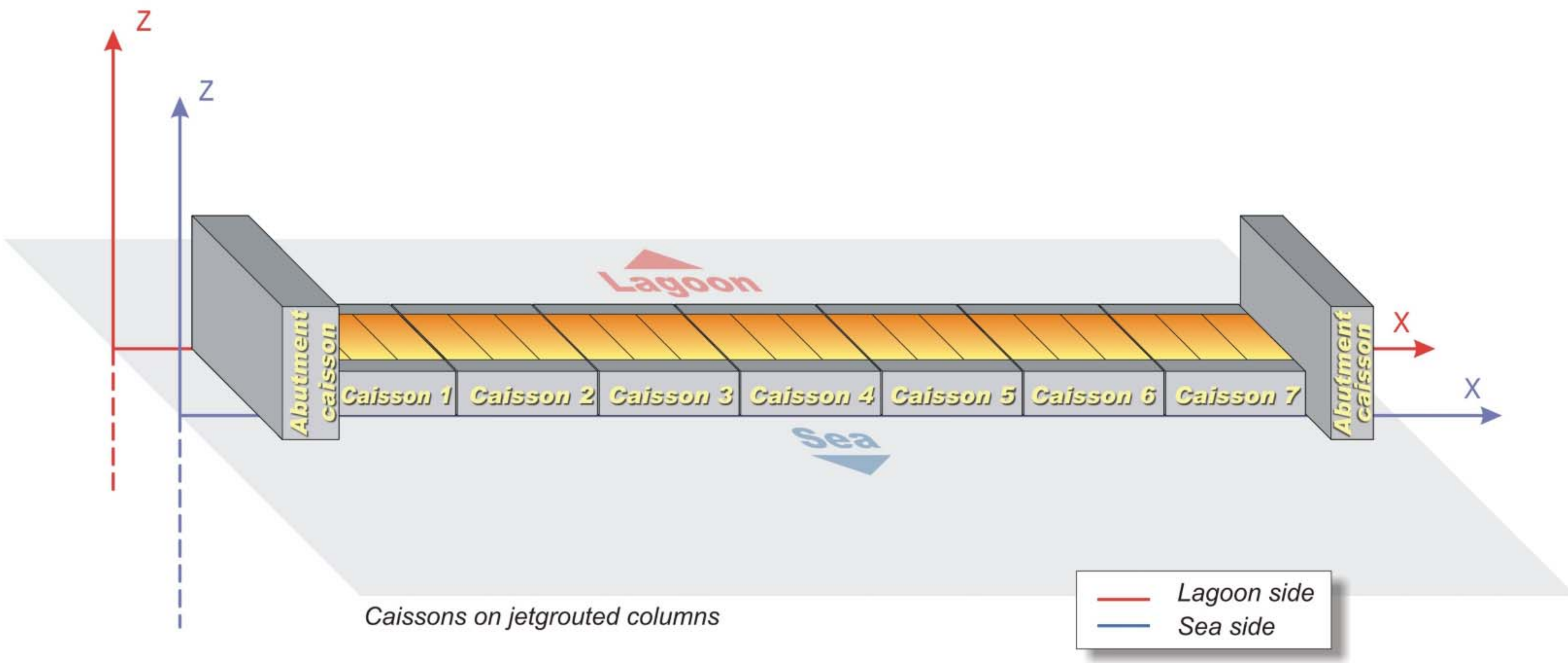
(*) Elasto-plastic-viscous soil model, Rocchi et al (2003)

TREPORTI INLET – CENTER OF TRIAL EMBANKMENT
COMPUTED* vs. MEASURED SETTLEMENTS

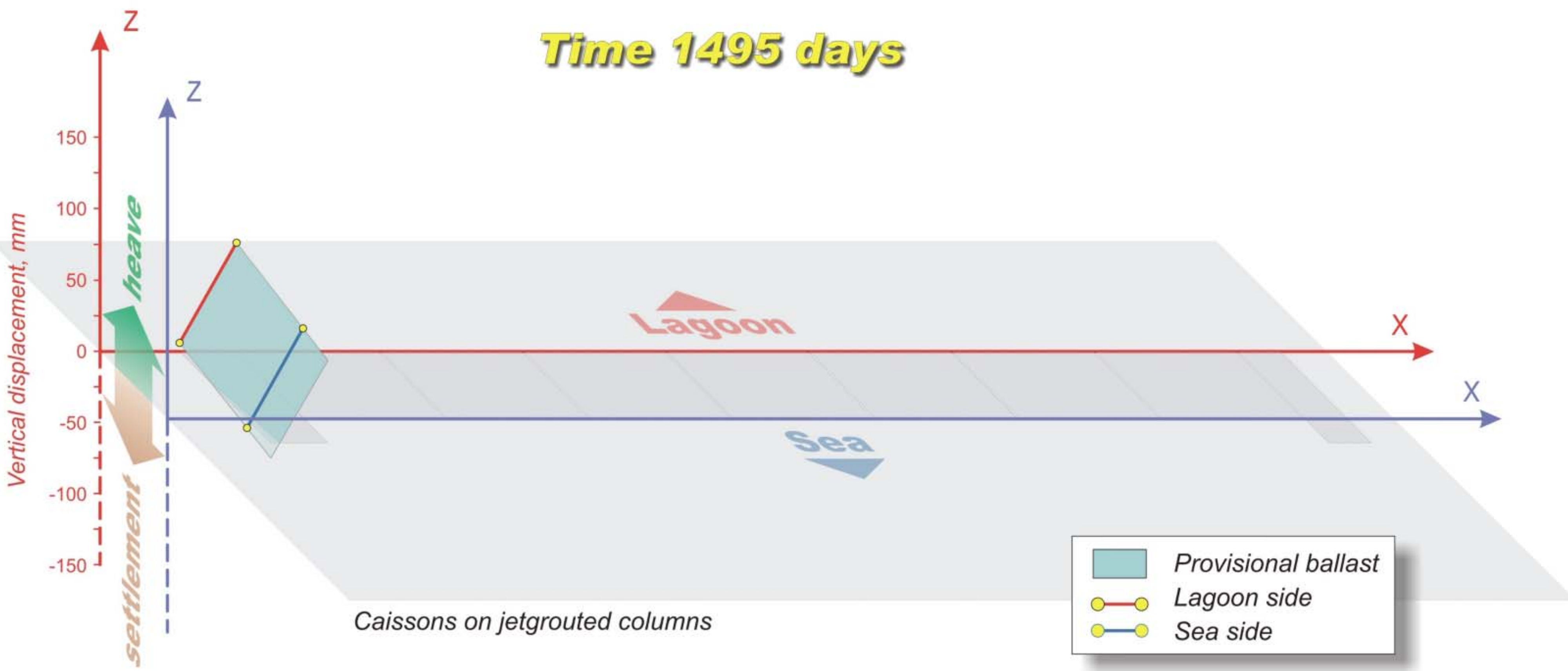


(*) Elasto-plastic-viscous soil model, Rocchi et al (2003)

THE MOSE SYSTEM
BARRIER AT TREPORTI INLET



THE MOSE SYSTEM: BARRIER AT TREPORTI INLET
COMPUTED CAISSONS' VERTICAL DISPLACEMENTS



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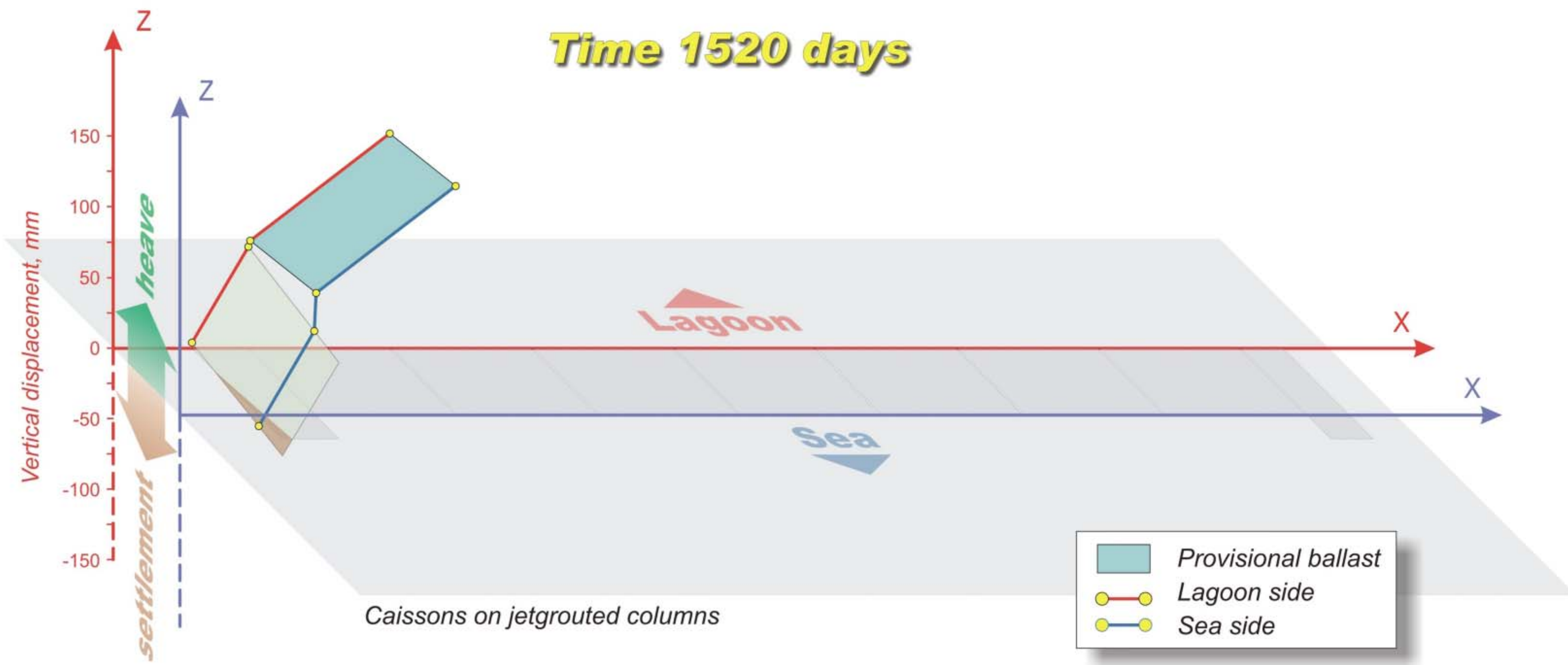

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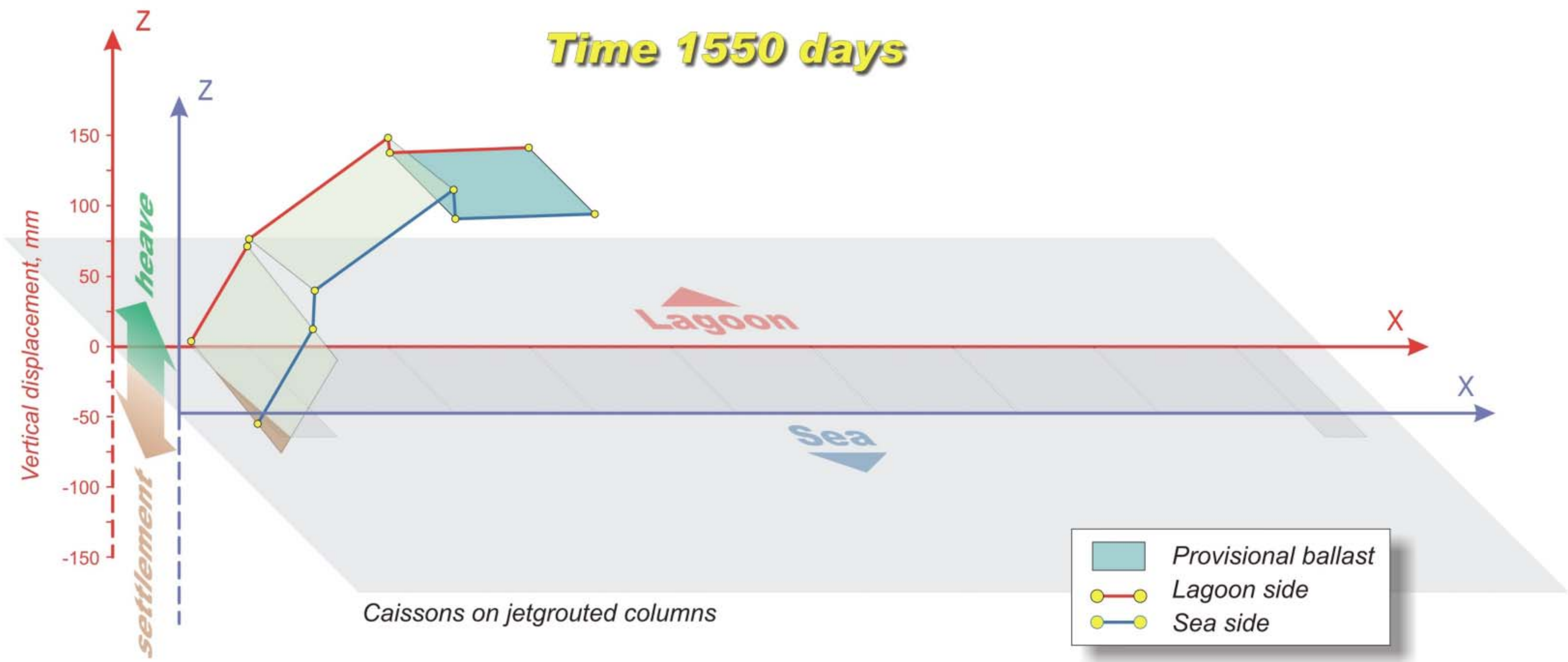

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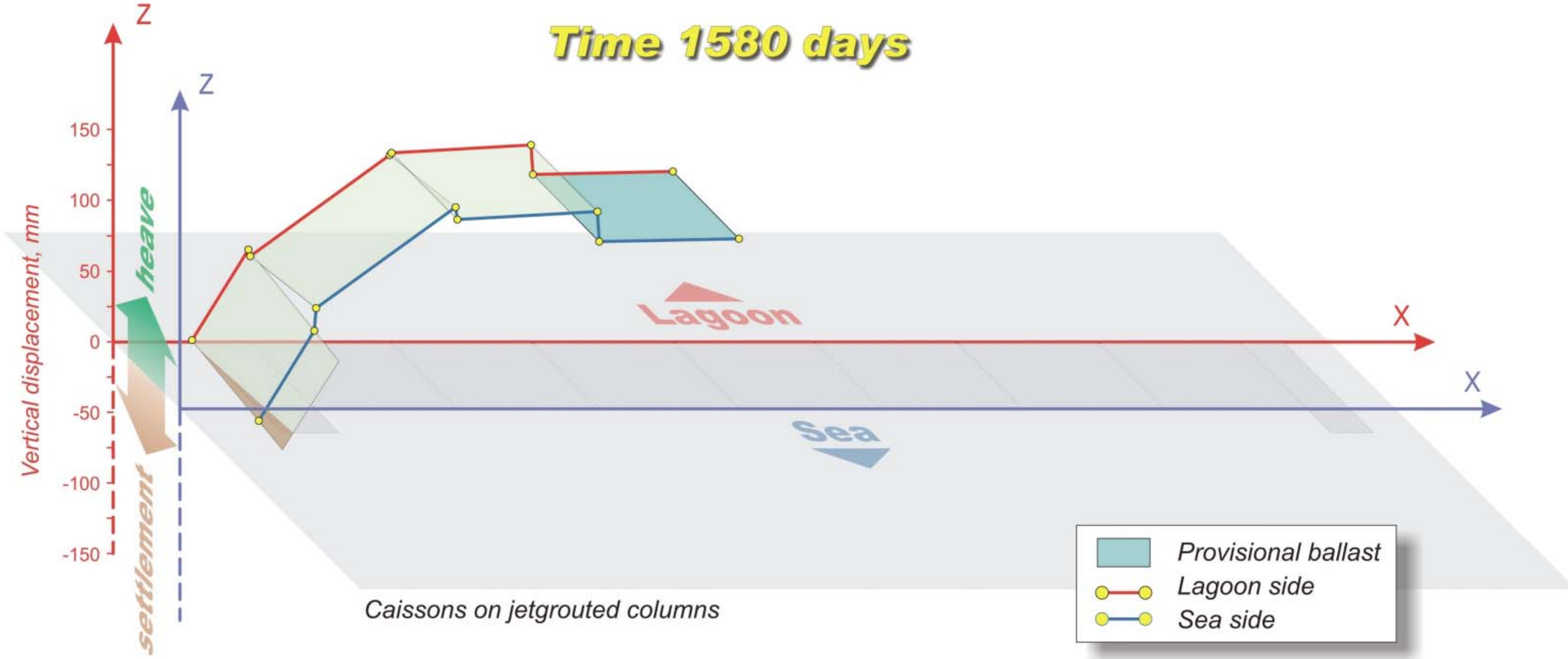
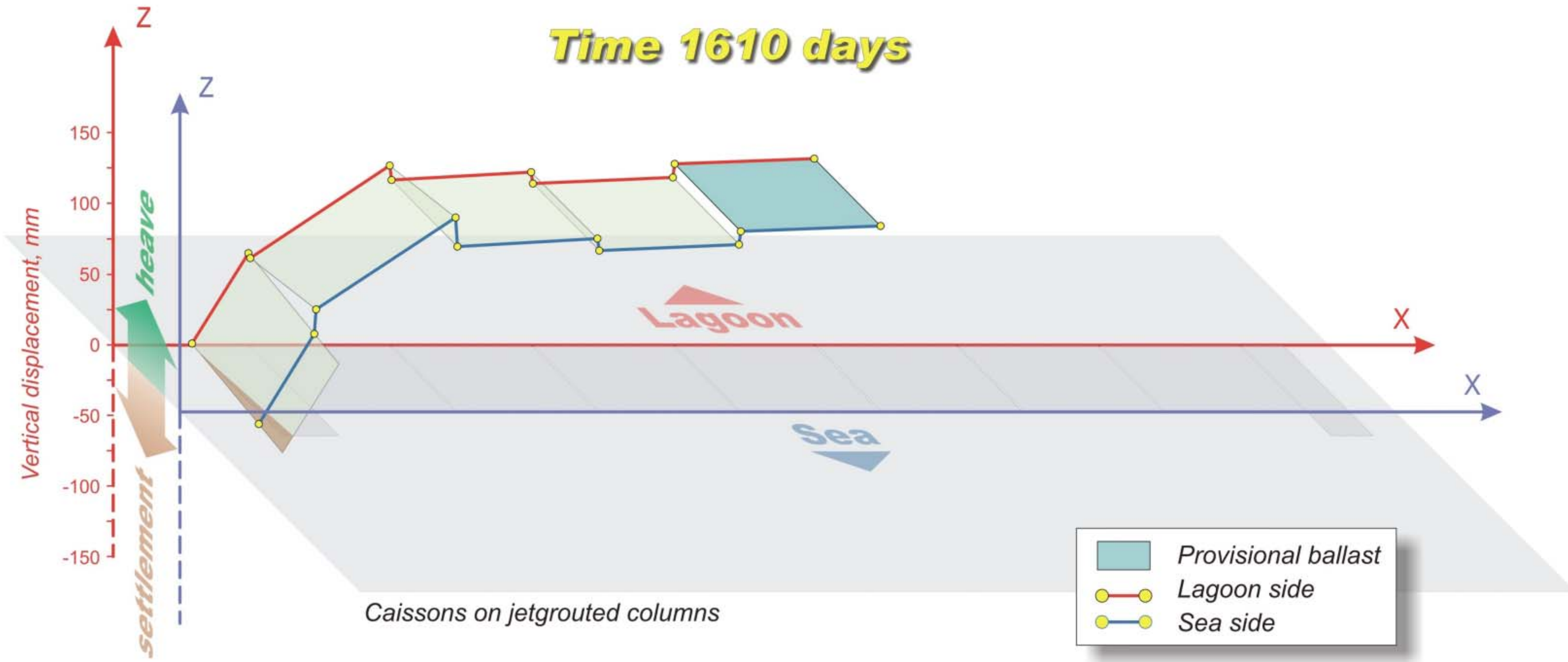


THE MOSE SYSTEM: BARRIER AT TREPORTI INLET COMPUTED CAISSONS' VERTICAL DISPLACEMENTS



Caissons on jetgrouted columns

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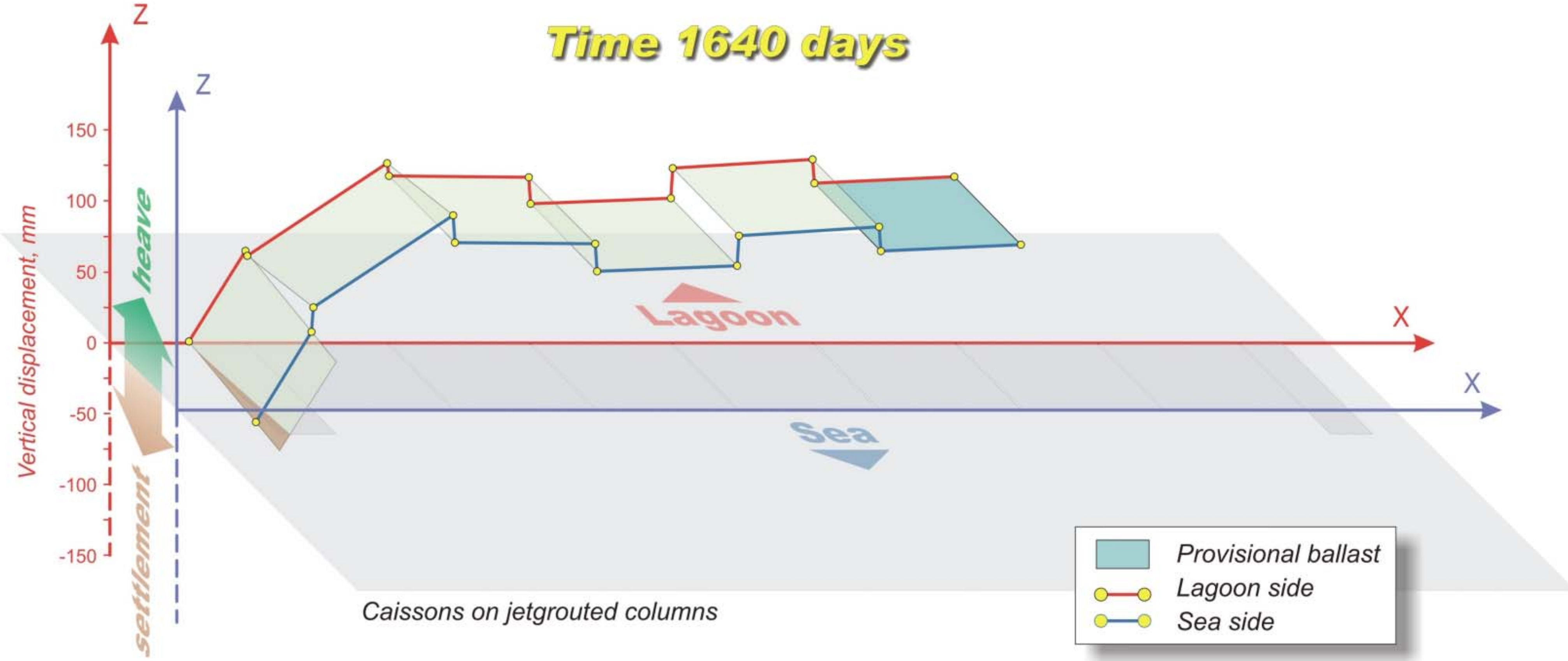

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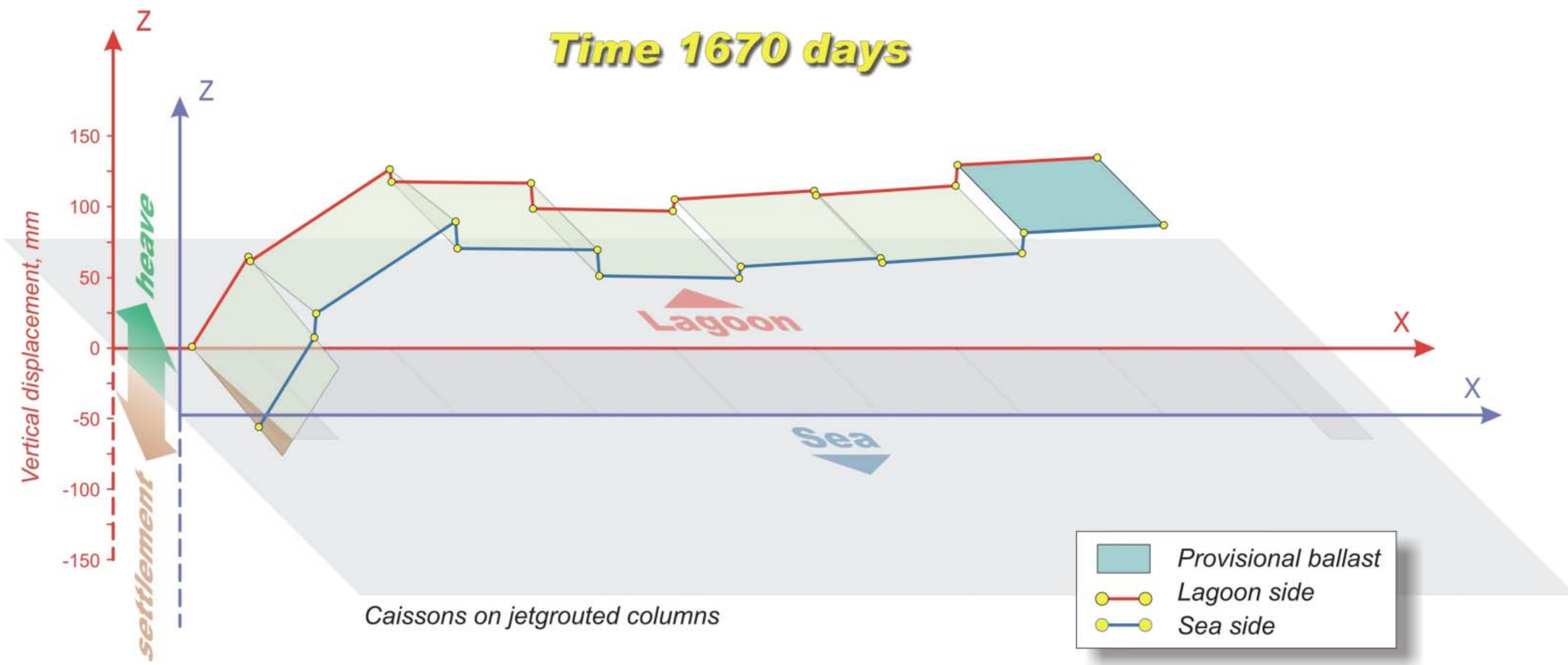

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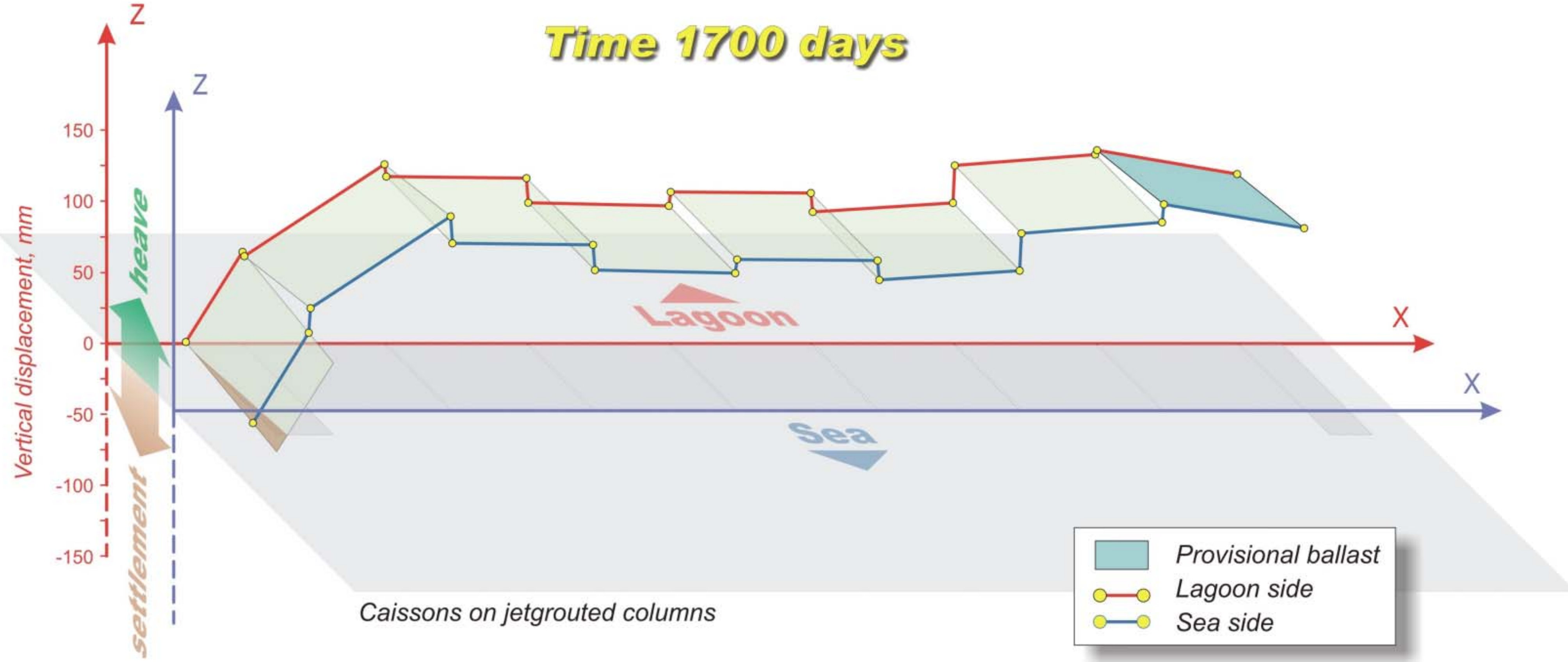

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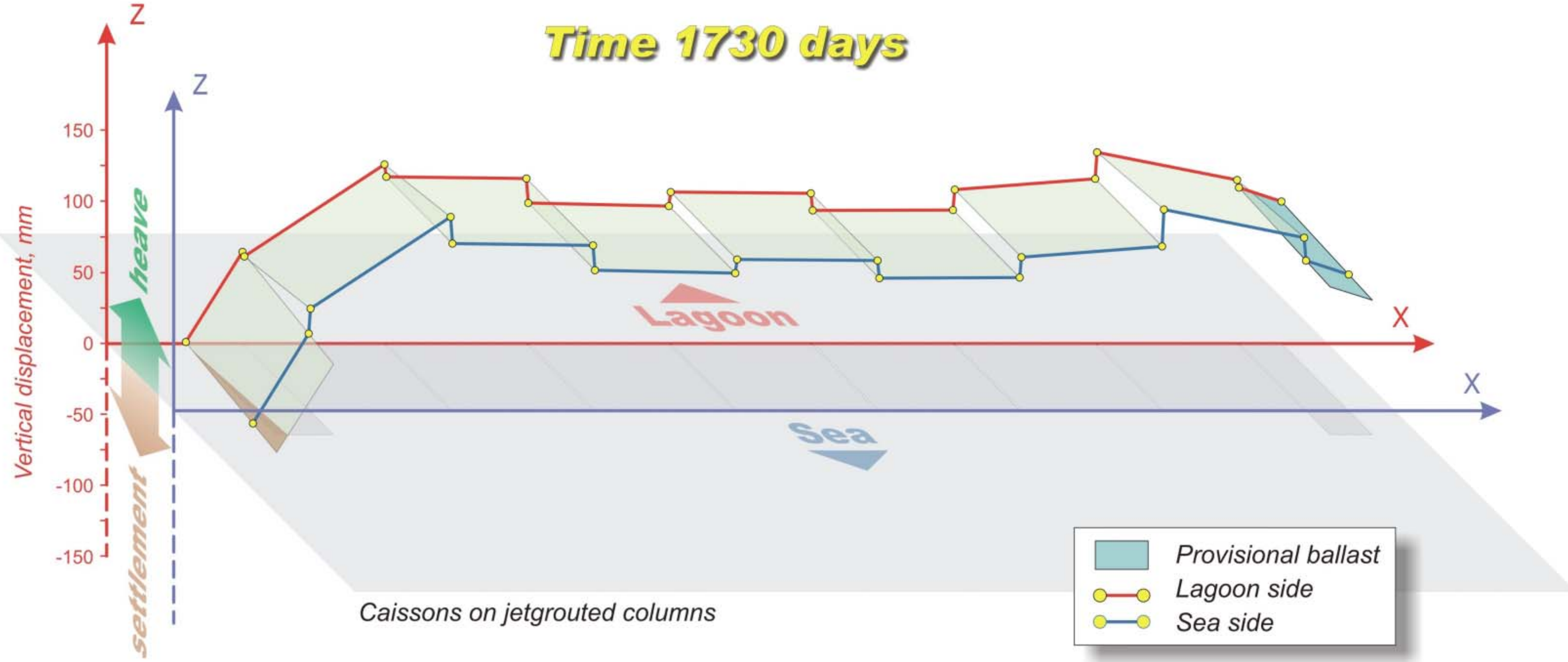

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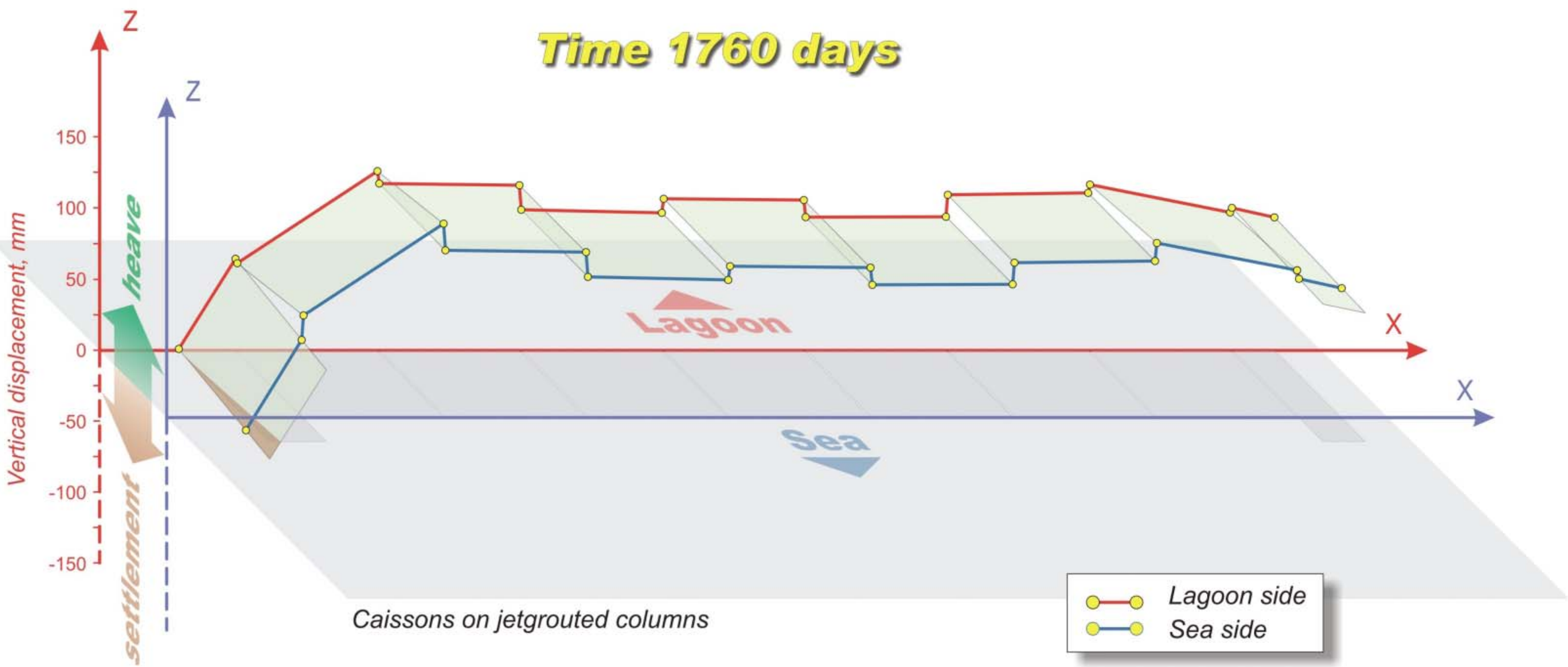

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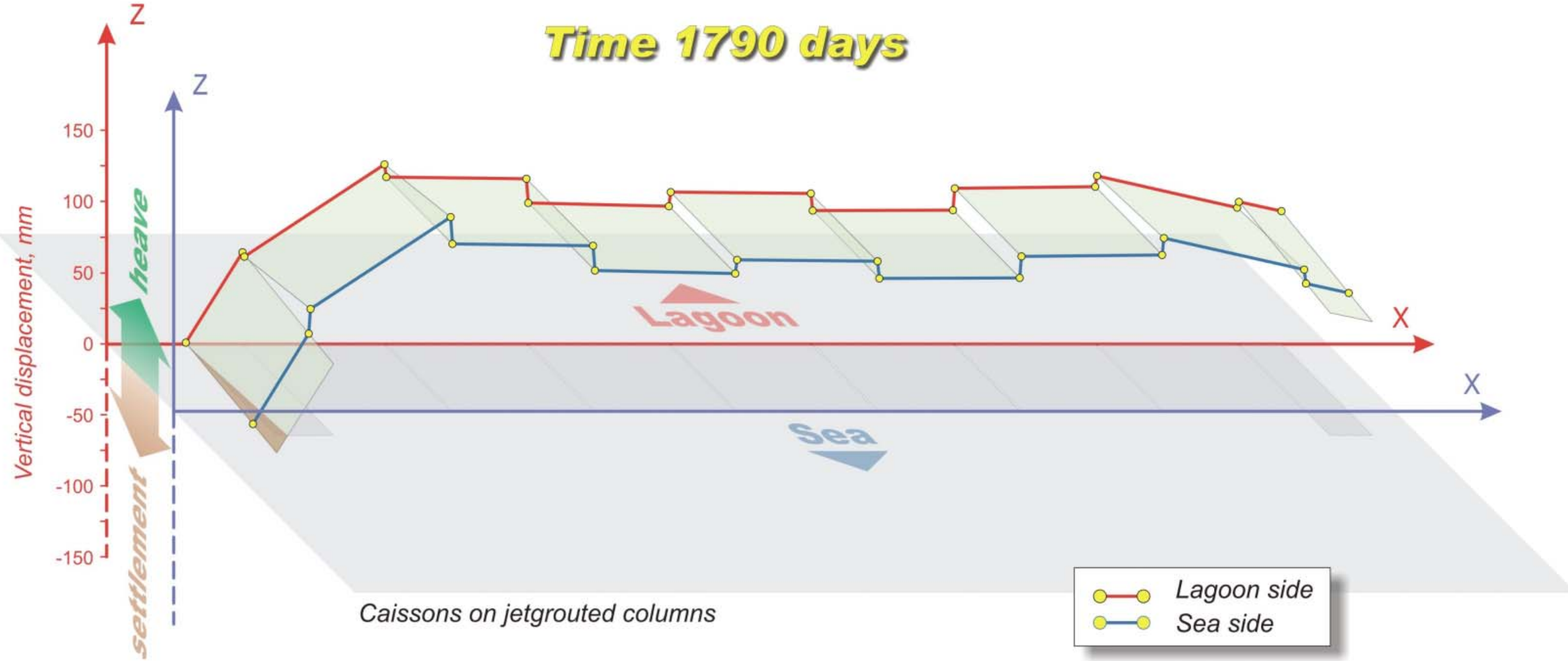

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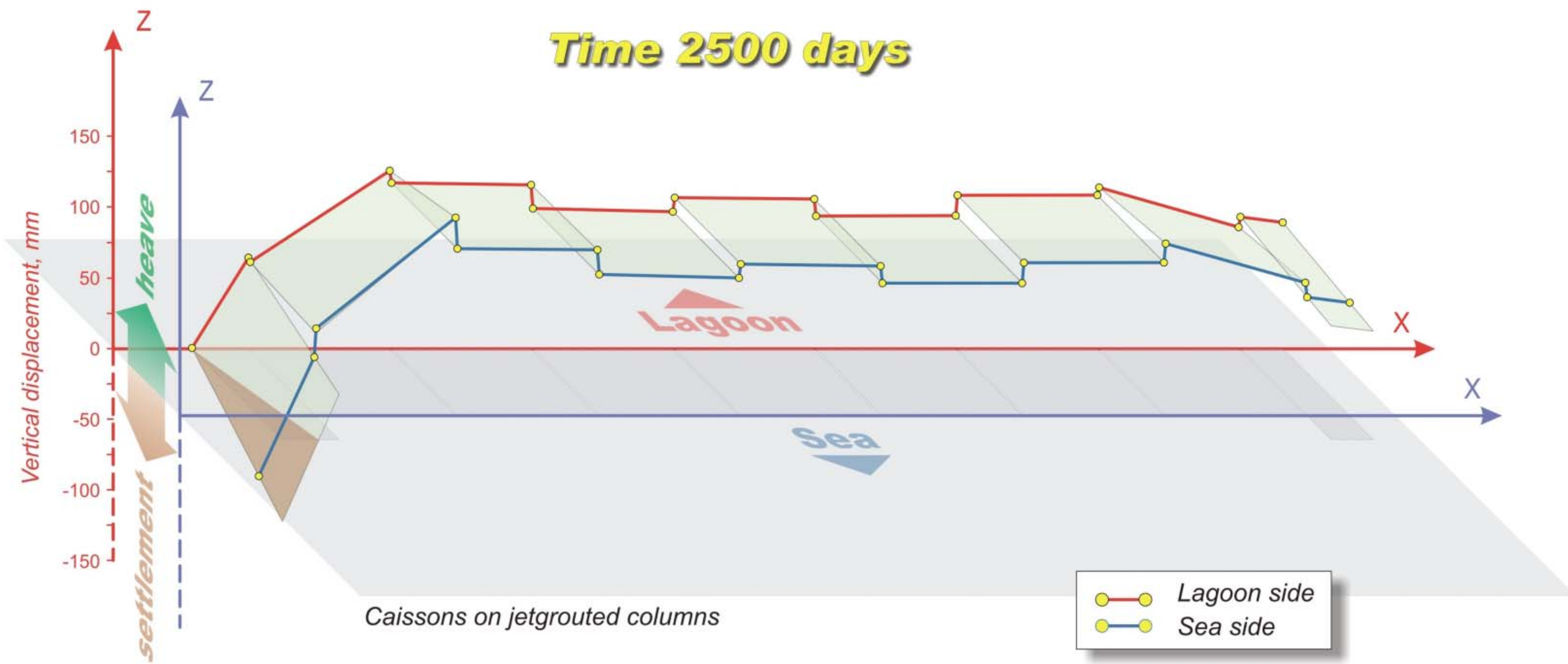

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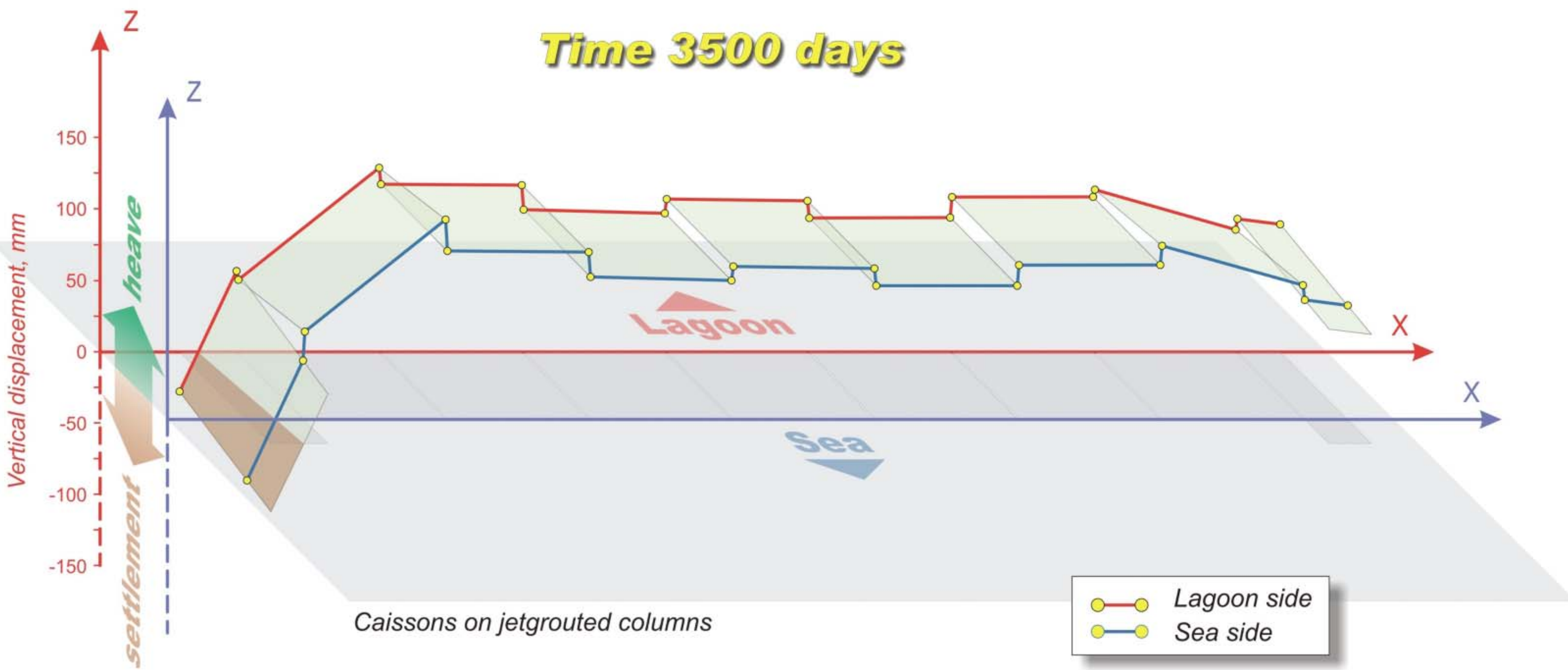

Caissons on jetgrouted columns

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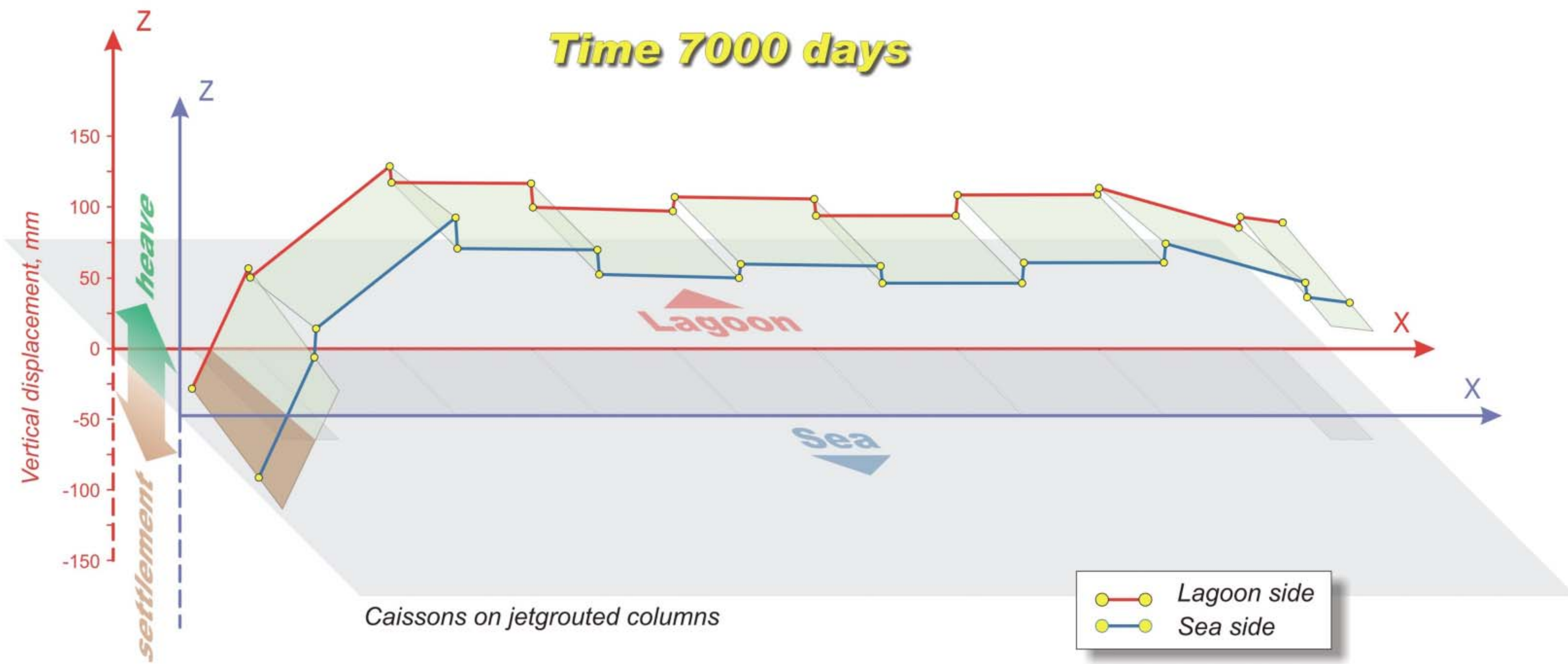

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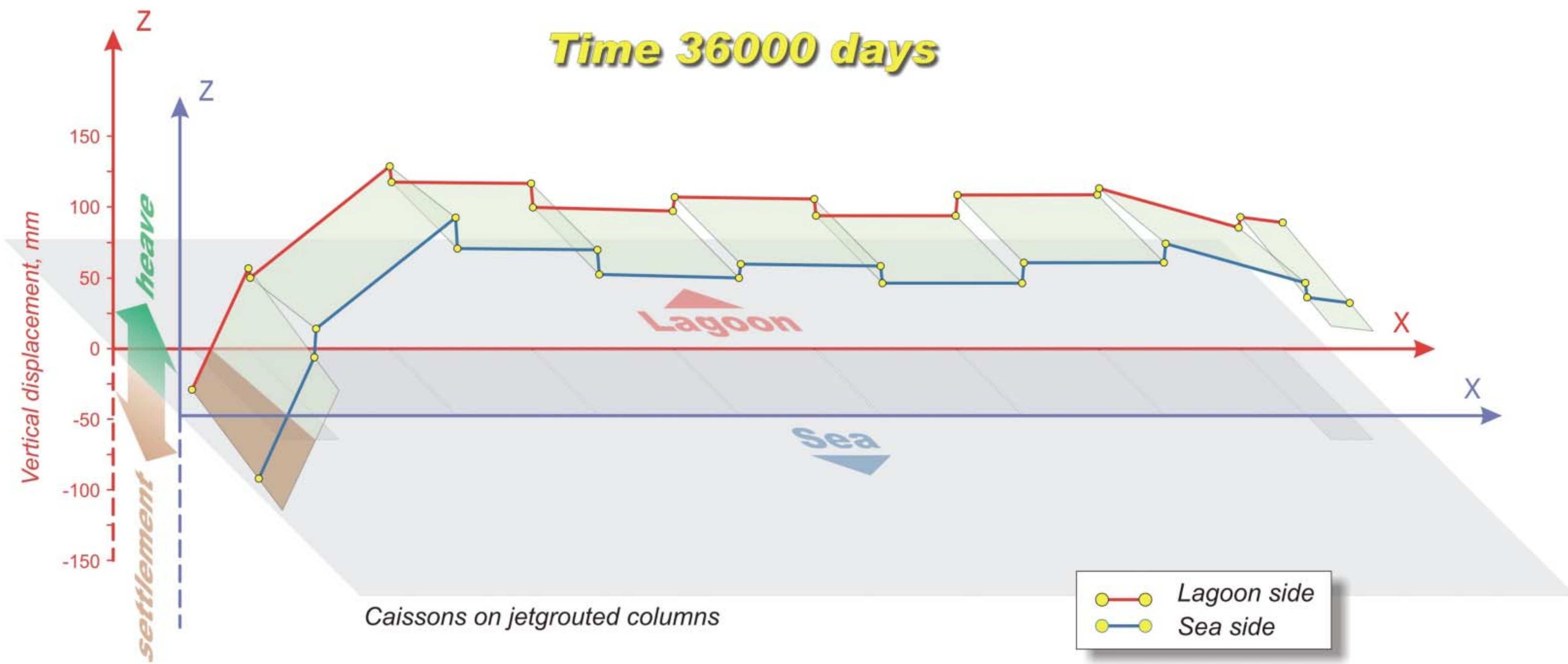

Caissons on jetgrouted columns

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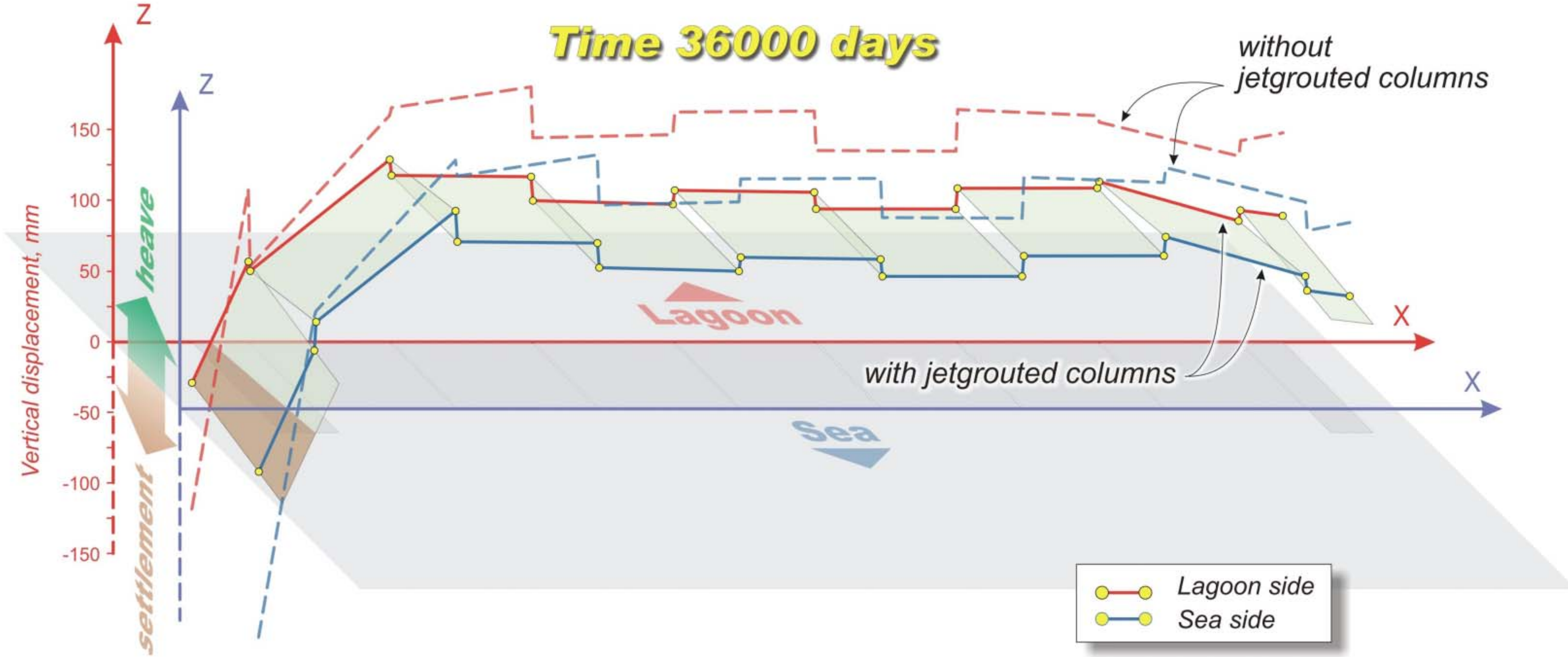


CAISSONS FOUNDATIONS: TRIAL FIELD

- **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 INSTRUMENTED 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

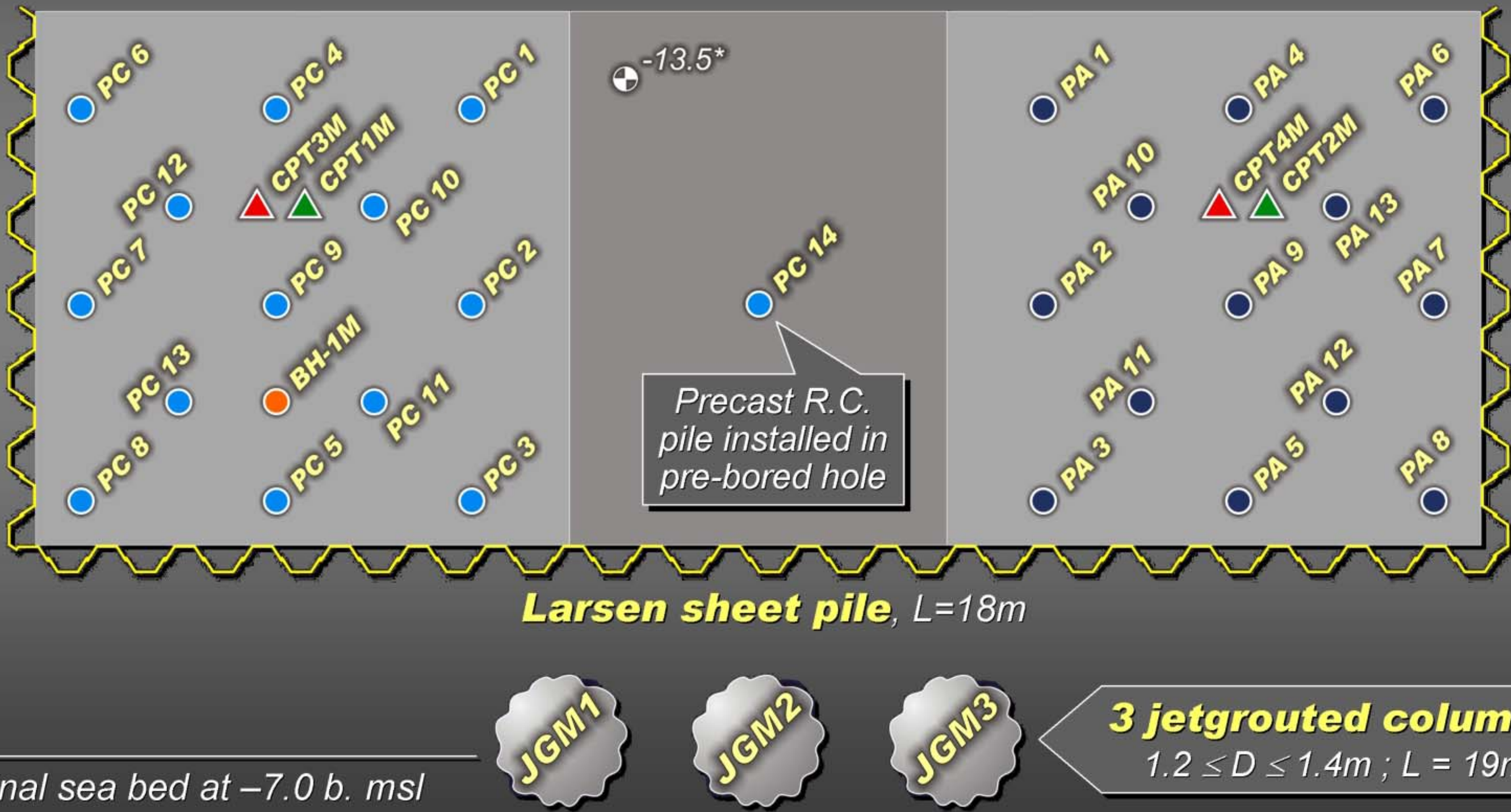
Quality control activities

- 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)
- Seismic tests aimed at checking columns' continuity

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



3 jetgrouted columns
$1.2 \leq D \leq 1.4m$; L = 19m

(*) Original sea bed at –7.0 b. msl

Lecture Outline

- Introductory remarks
- Protection from high tides
  - Historical background
  - Selected solution
- Lagoon subsoil
- Foundation problems
- <u>Closing remarks</u>

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)

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**

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: end of year 2006
- **Prefabrication of barriers caissons:**
  to be started in autumn 2006

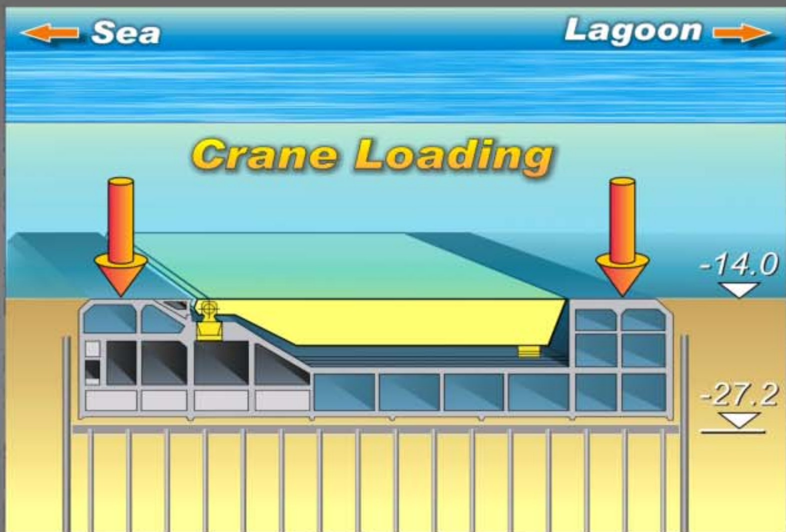
THREE BARRIERS FACT FILE:

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

MALAMOCCO BARRIER ON SETTLEMENT REDUCING PILES*
COMPUTED DISPLACEMENTS**

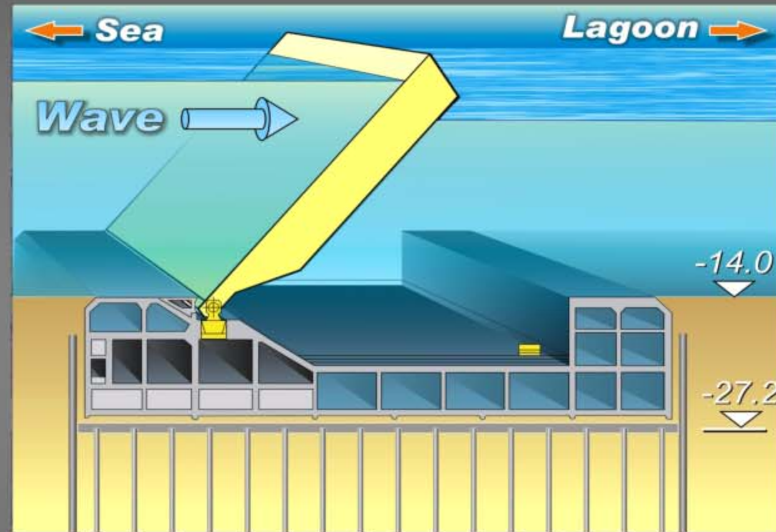
GATE CLOSED, CRANE IN OPERATION

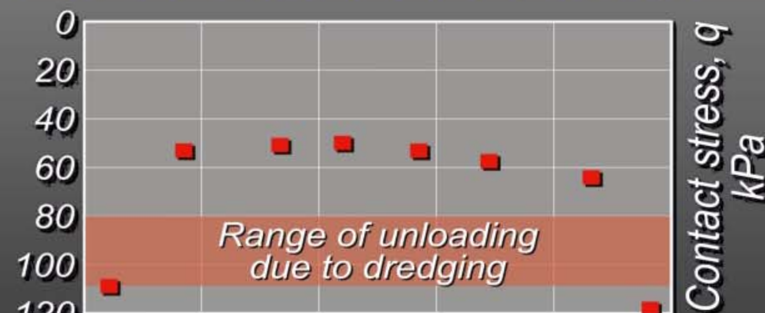
SEA	LAGOON
s_v = 44.0 mm	s_v = 41.5 mm
s_h = 0	



GATE OPEN, WAVES ACTION

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

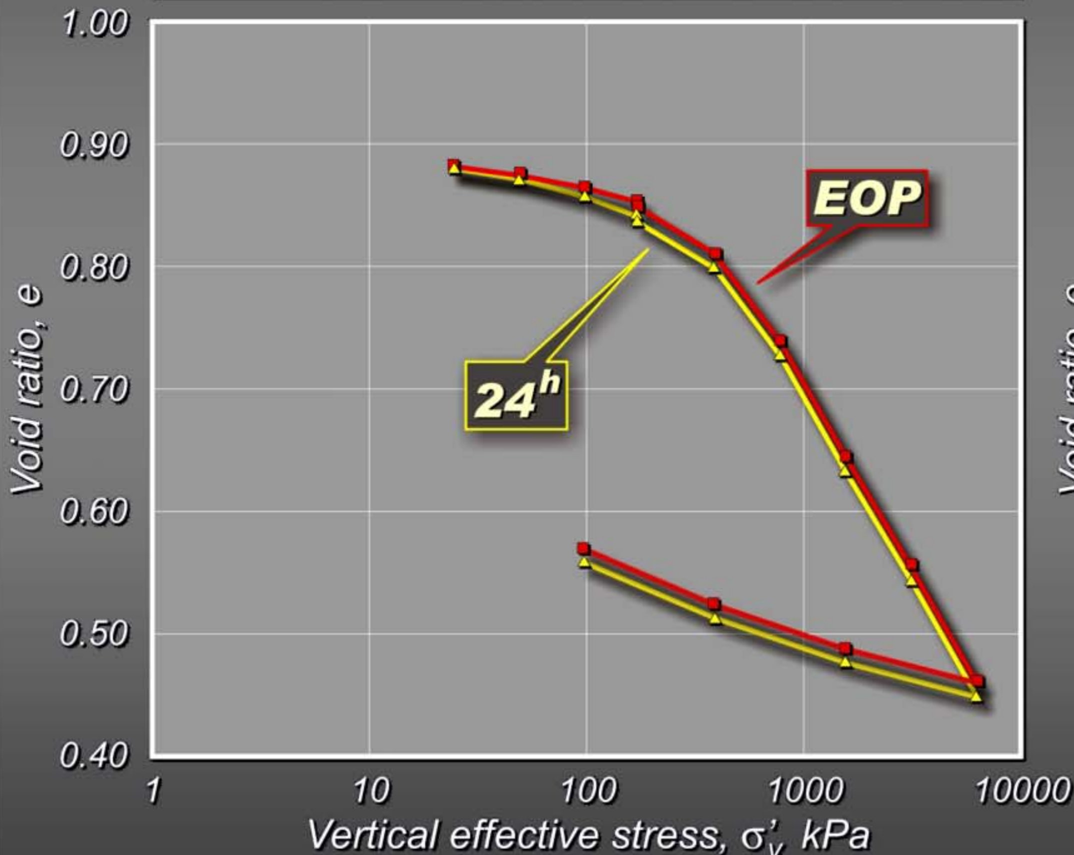




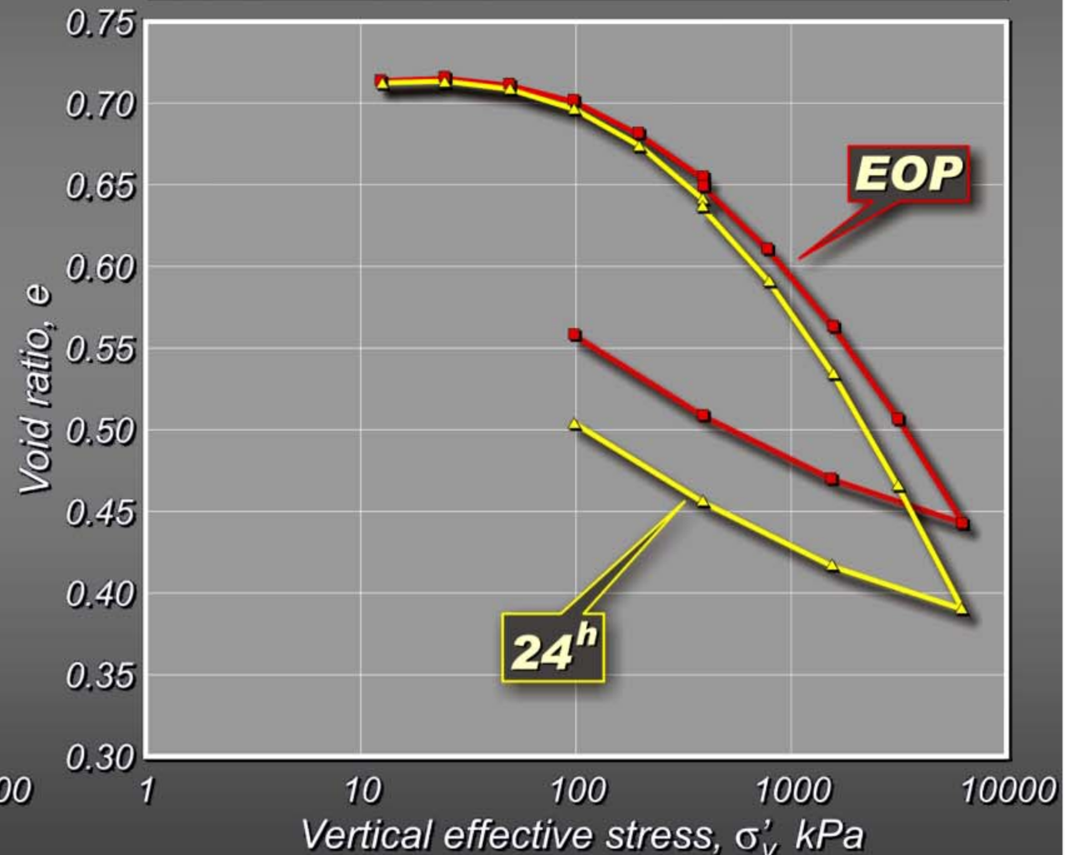
(*) L ≅ 19m long - (**) FE-2D elastoplastic analyses using PLAXIS code

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.

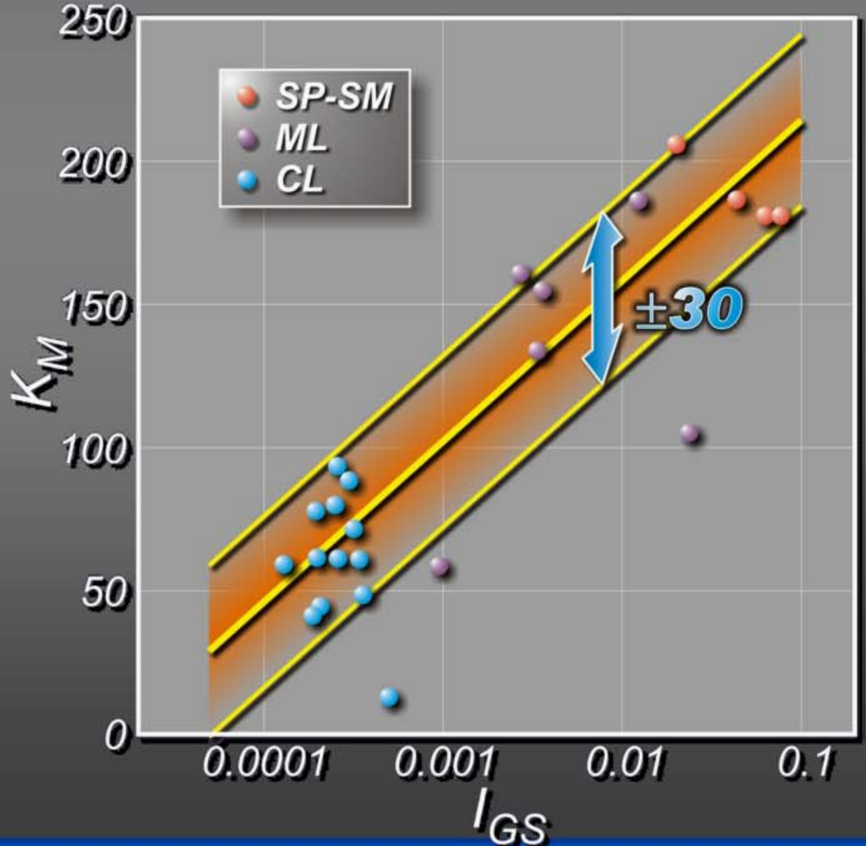
VENICE LAGOON DEPOSITS
CONSTRAINED MODULUS

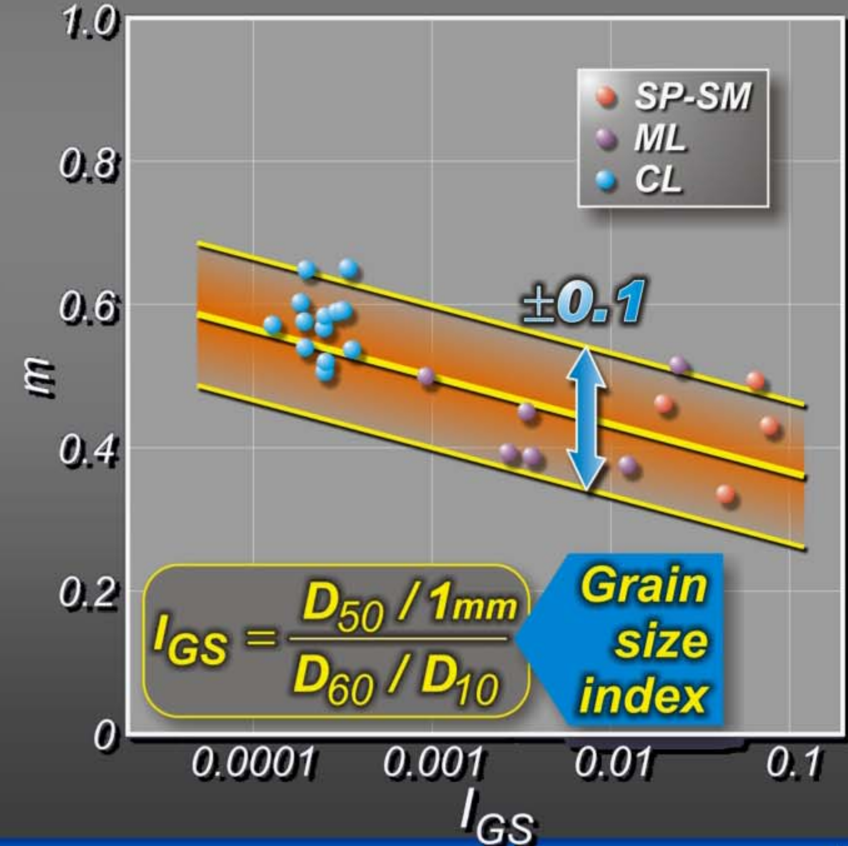
Simonini (2004)

$$\frac{M}{p_a} = K_M \cdot \left(\frac{\sigma'_v}{p_a}\right)^m$$

K_M = Modulus number

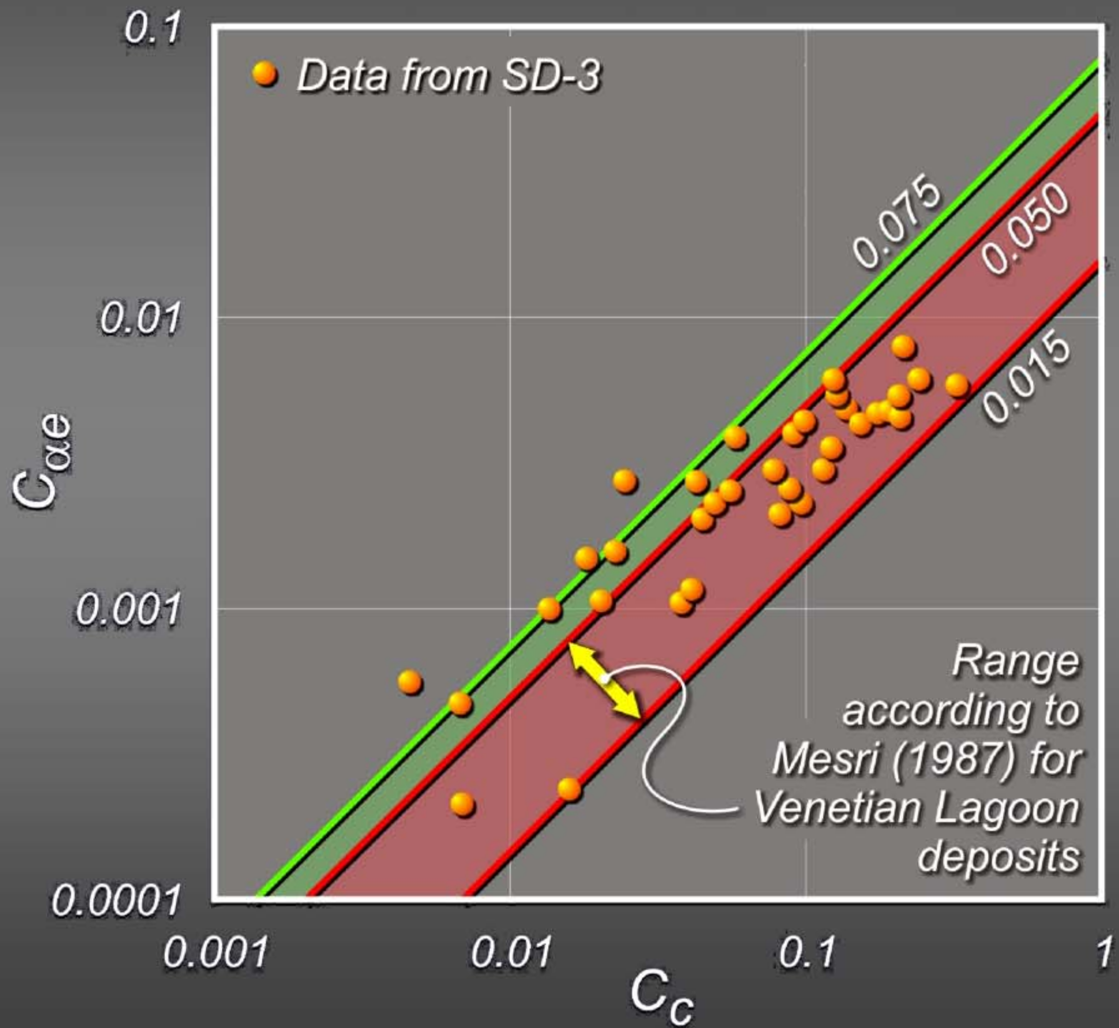
m = Modulus exponent





PRIMARY AND SECONDARY COMPRESSIBILITY MEASURED IN SITU

Ricceri et al. (2004)



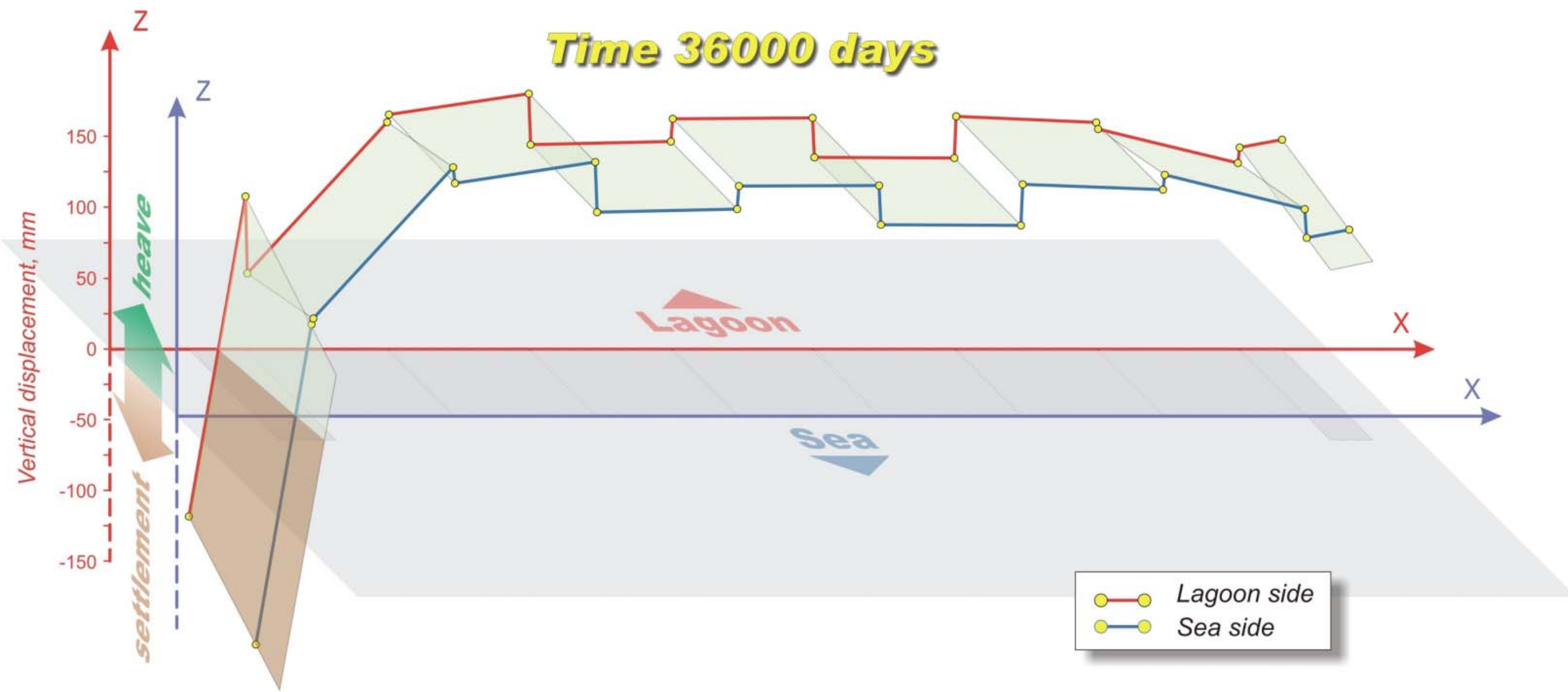
$$C_c = \frac{de}{d(\log_{10} \sigma'_v)}$$

Coefficient of primary compression

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

Coefficient of secondary compression

THE MOSE SYSTEM: BARRIER AT TREPORTI INLET
COMPUTED CAISSONS' VERTICAL DISPLACEMENTS



WITHOUT JET GROUTING TREATMENT

SAFEGUARDING VENICE LAGOON FROM HIGH TIDES

- **MOBILE BARRIERS SYSTEM:**

  *Protect Venice and other lagoon's settlements against tides exceeding +1.1 m above msl.**

- **INSULAE PROJECT:**

  Raising elevation of banks sidewalks and pavements, protection against tides lower than +1.1 above msl.

(*) Ensuring normal port's activities