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Working with water

Historical Experience of Vertical Breakwaters (in the UK)

William Allsop

HR Wallingford & University of Southampton

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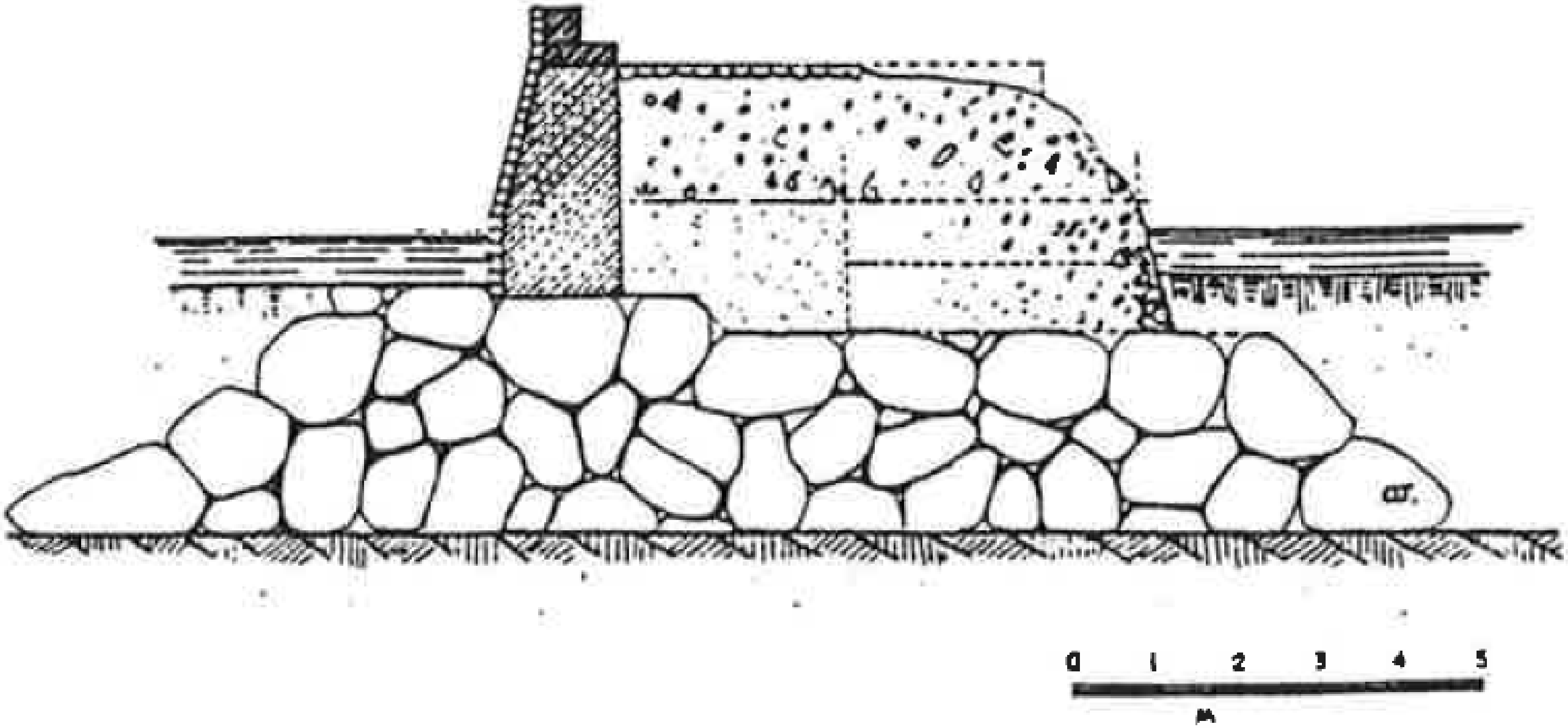
Historical context

"Italy is often considered as a mother country of vertical breakwaters for harbour protection …the technology of vertical concrete walls was introduced 2000 years ago by the Roman harbour engineers in contrast with the Greek tradition of rubble mound breakwaters."

Franco L. (1994) *Vertical breakwaters: the Italian experience*, Coastal Engineering, Vol. 22, pp31-55, Elsevier Science, Amsterdam.

Classic "vertical" breakwaters



Composite breakwater at Claudius Port (Rome) with concrete superstructure using ship hulls as lost forms

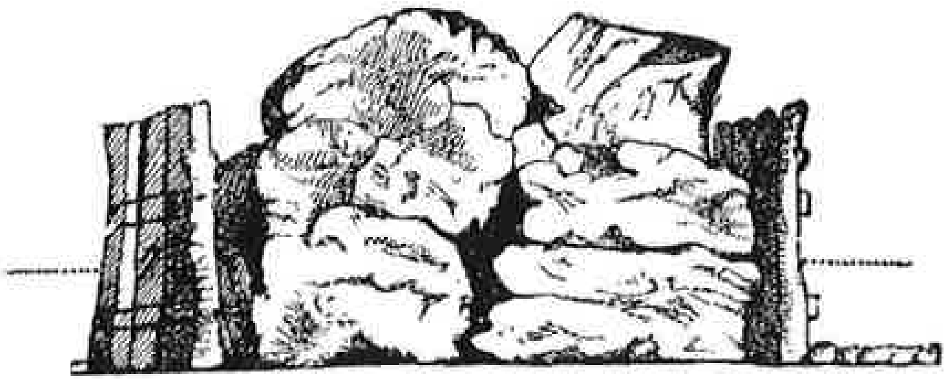
Classic "vertical" breakwaters

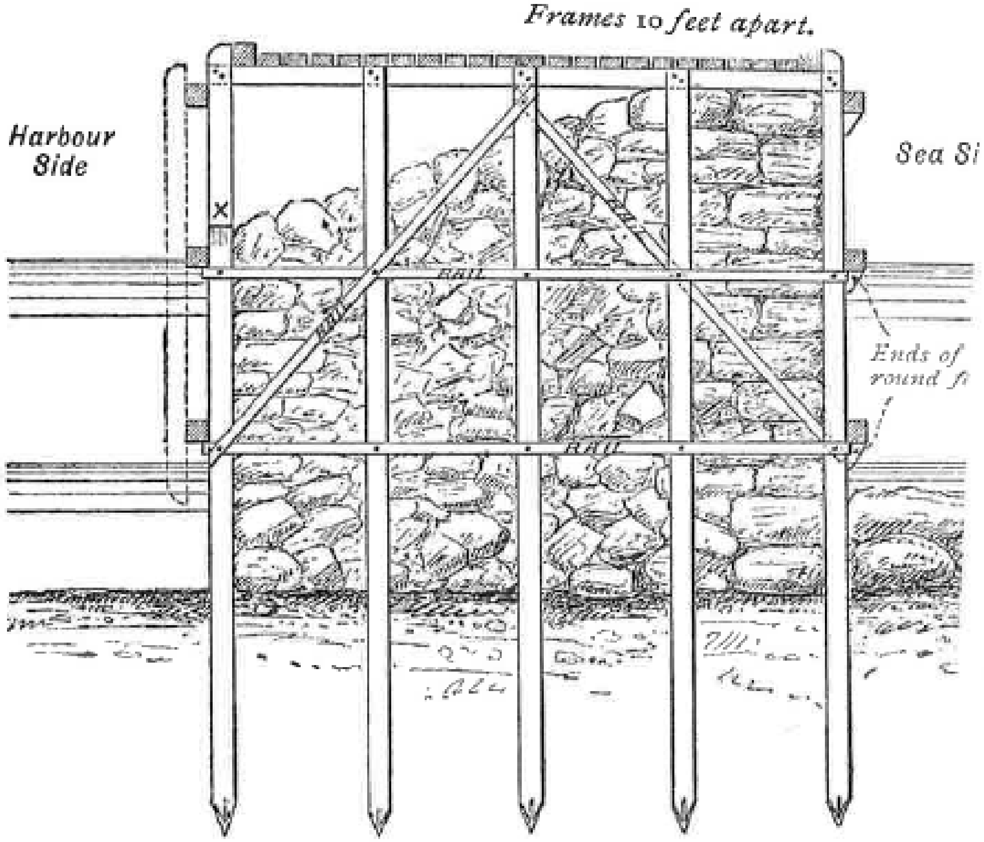
Detached vertical breakwater (blockwork) at the Venetian port at Dubrovnik (circa 1500s).

Armour on the seaward face was added later.

Classic “vertical” breakwaters

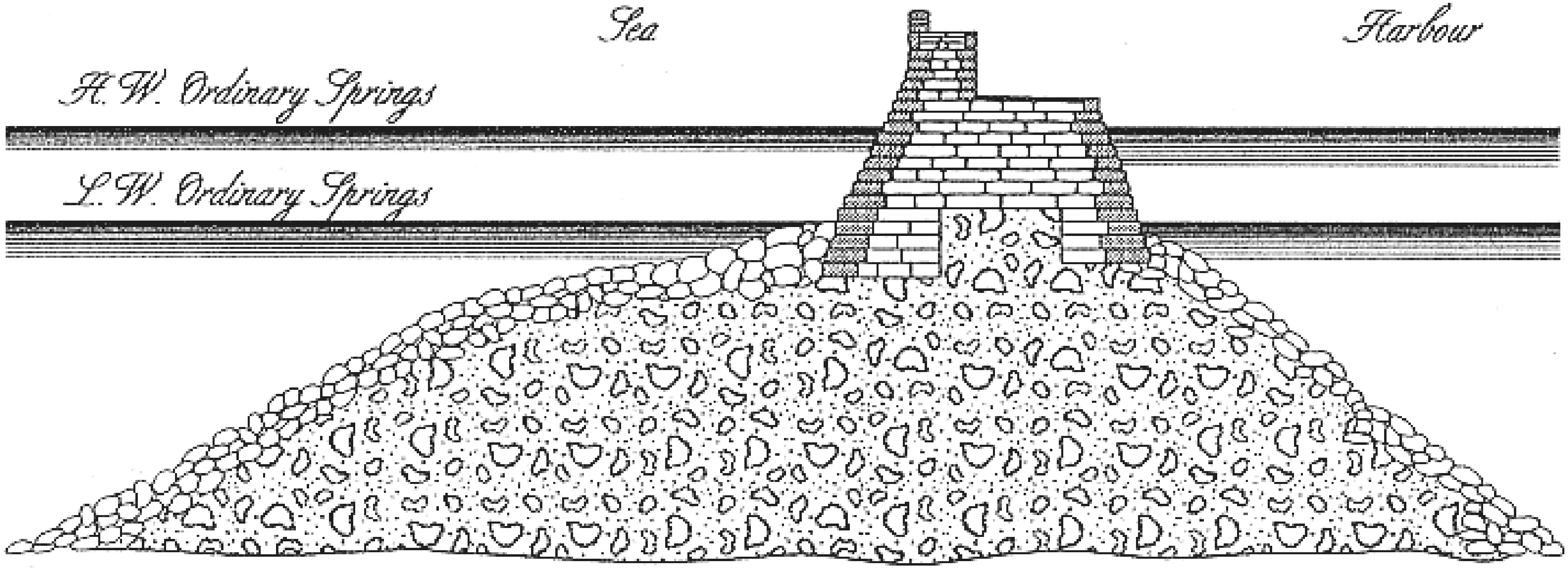
The “Cob” breakwater at Lyme Regis, 16th C, Braye & Tatham (1992)





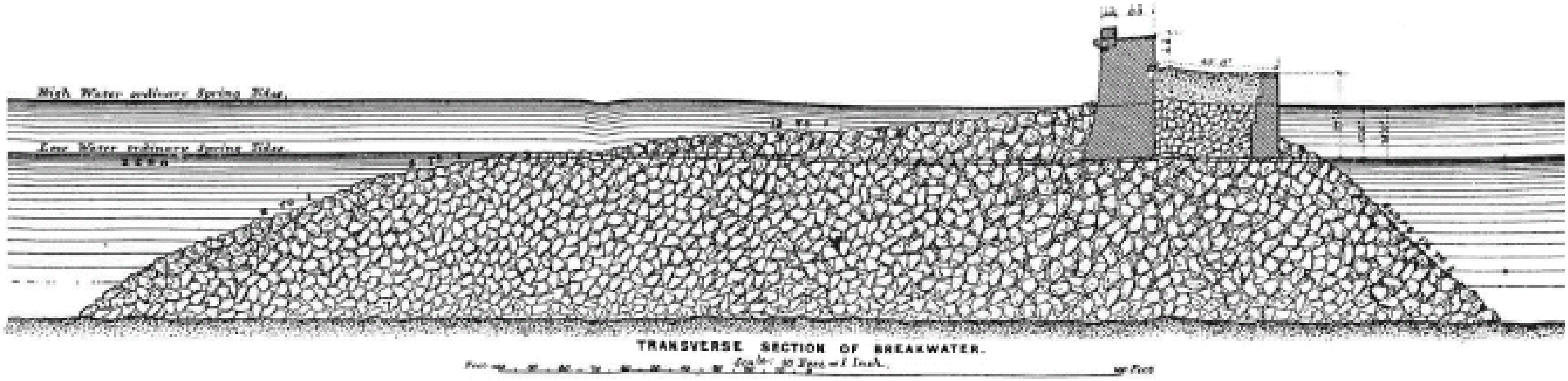
Typical timber frame with rubble hearting, Braye & Tatham citing Shield (1895)

Classic "vertical" breakwaters

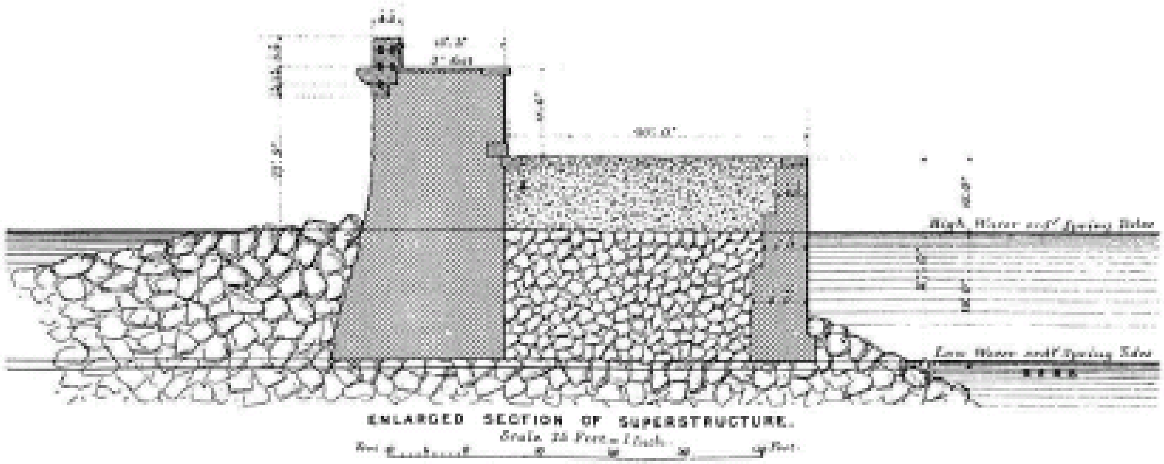


Original design for Alderney (c. 1845), showing foundation mound up to just below low water, stone blockwork walls, un-cemented fill

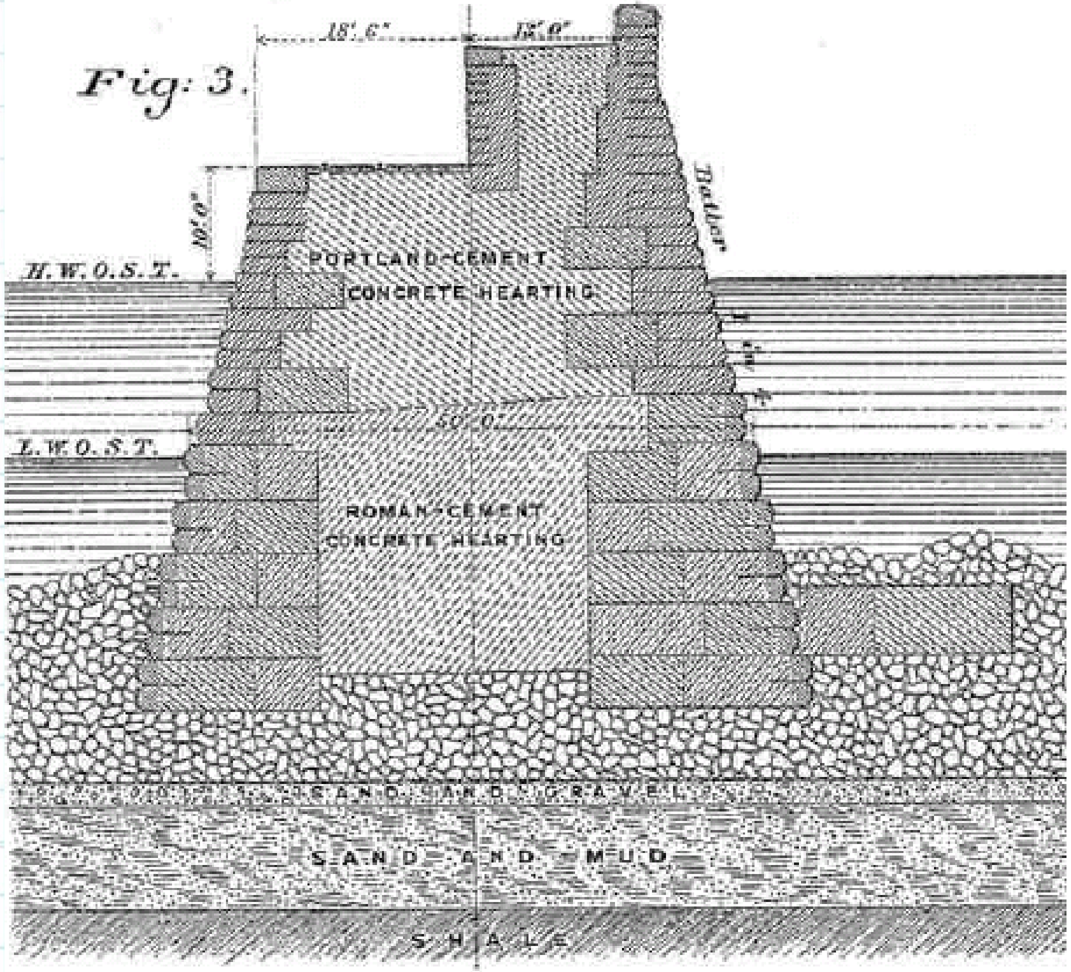
Classic “vertical” breakwaters



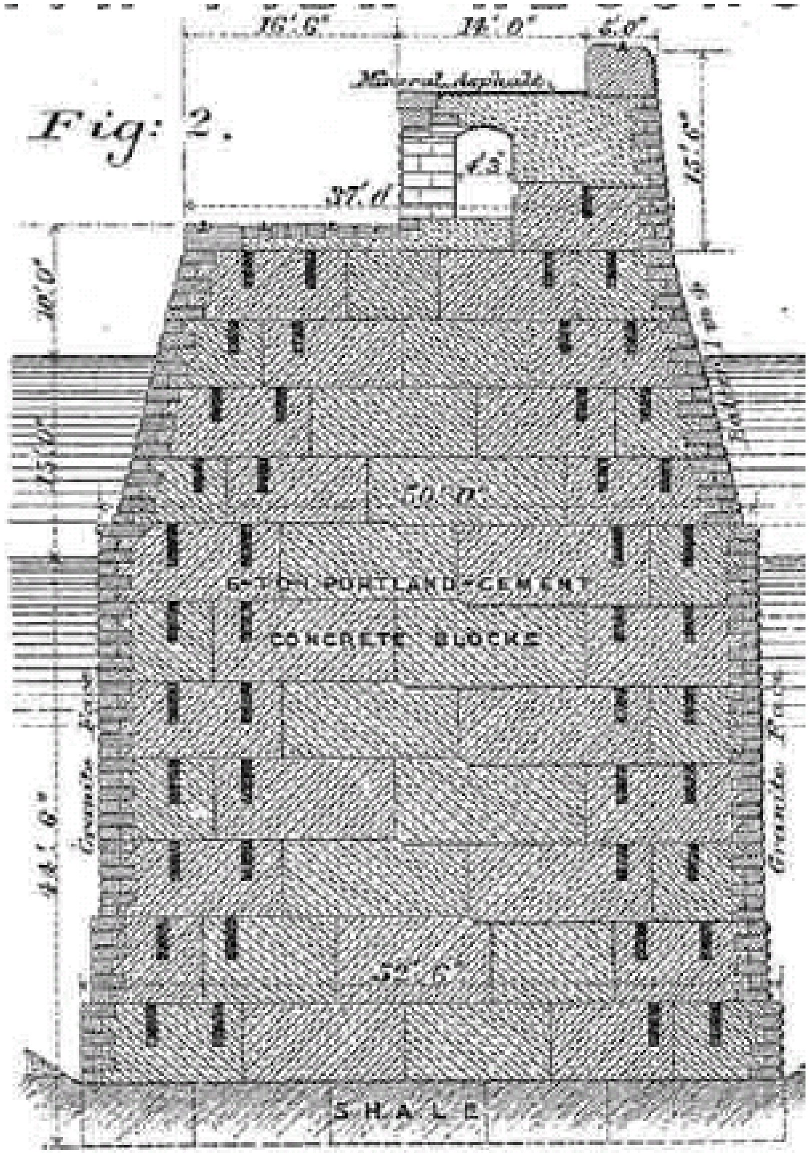
Wide mound to break waves before hitting the wall, but high mound can cause (longer) waves to shoal up and break impulsively against the wave wall



Classic "vertical" breakwaters



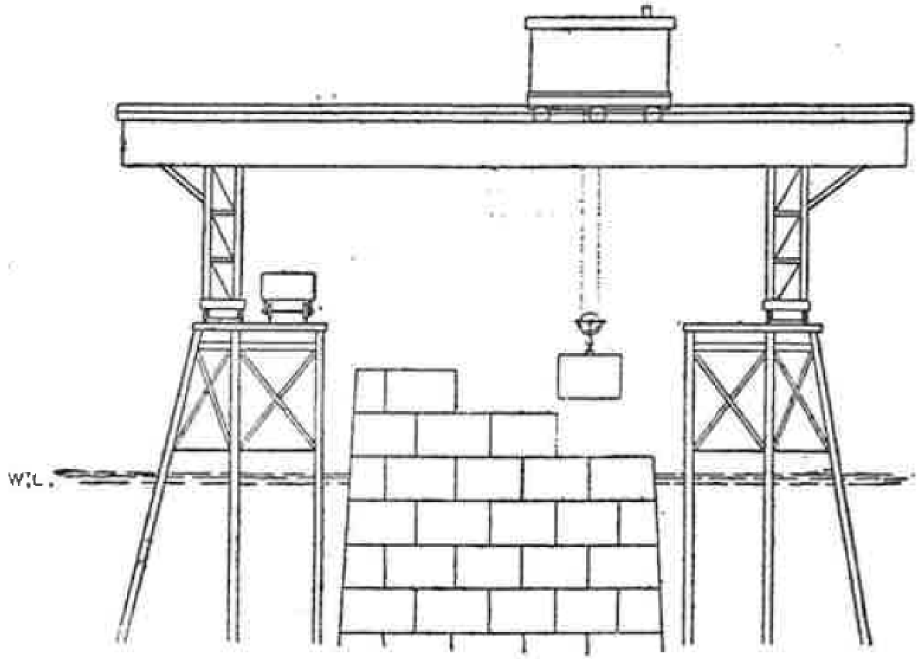
SECTION OF OLD STRUCTURE.

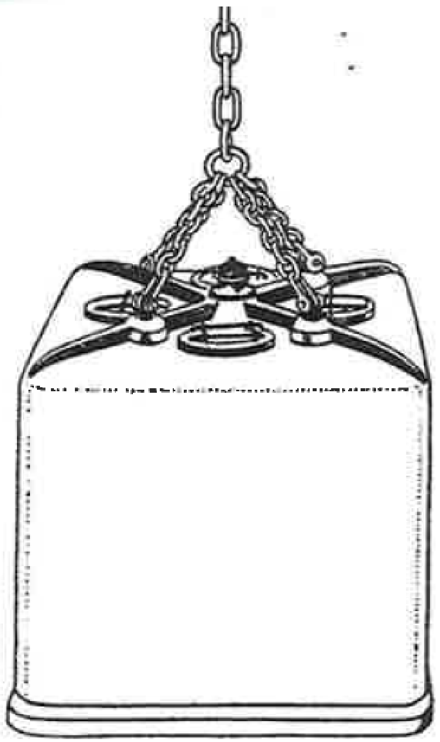


SECTION OF NEW STRUCTURE.

New Tyne North Pier, 1899

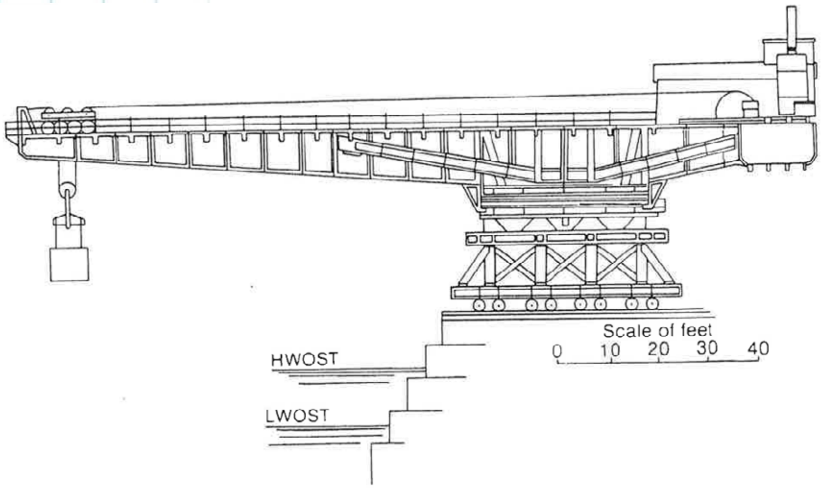
Construction methods, mid 1800s





Construction tools, including placement frames and travelling gantry, diving bell for mound preparation

Construction methods, mid / late 1800s



"Titan" cranes for block placement, here used at Peterhead South Breakwater

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Tangier Breakwater, 1661-1684

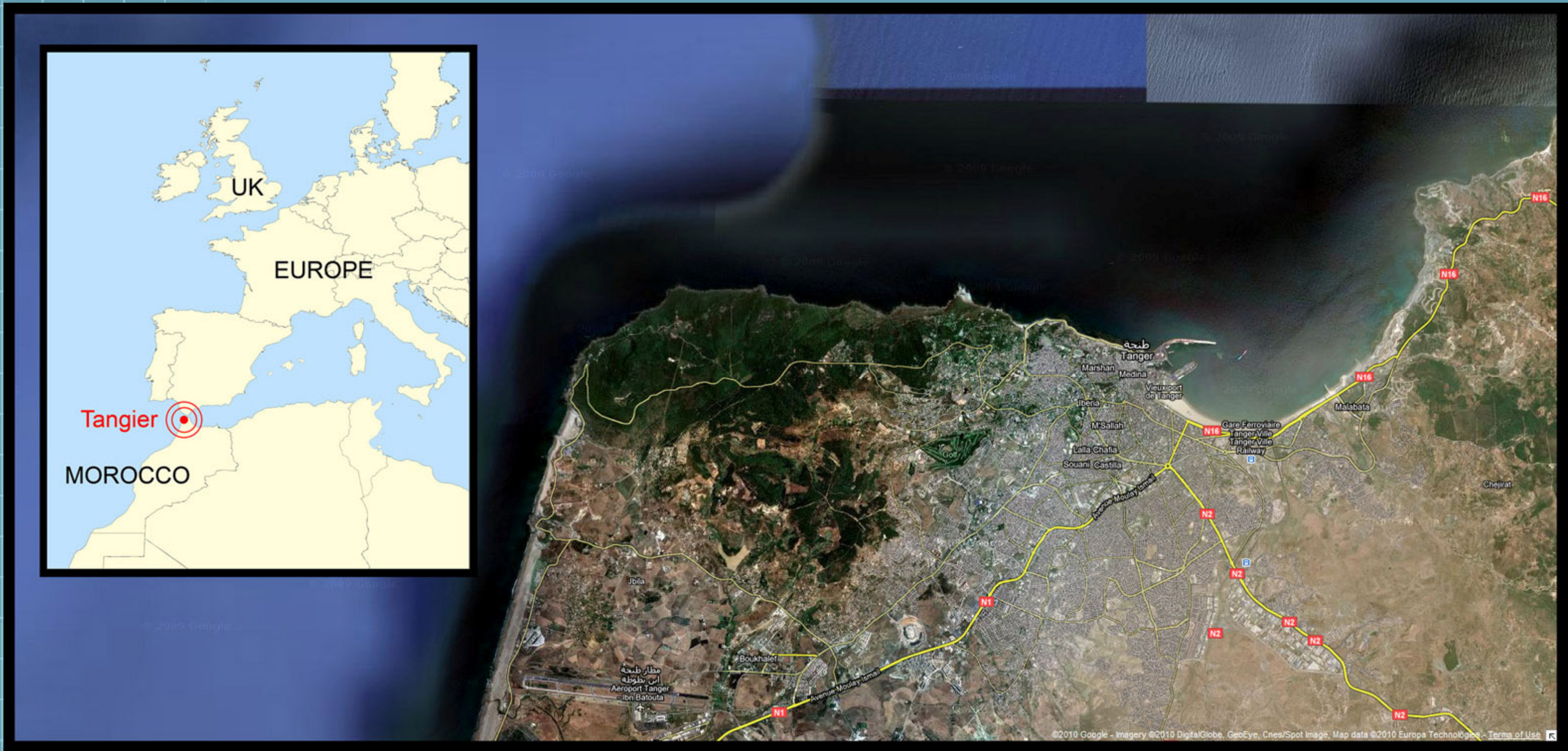
Routh EMG (1912) *Tangier: England's lost Atlantic outpost, 1661-1684,* (Chapter 17: The Mole and Harbour), John Murray, London.

Context of the Mole at Tangier

"The story of the English Occupation of Tangier would be incomplete without some account of the building of the Mole, the greatest engineering work till then attempted by Englishmen."

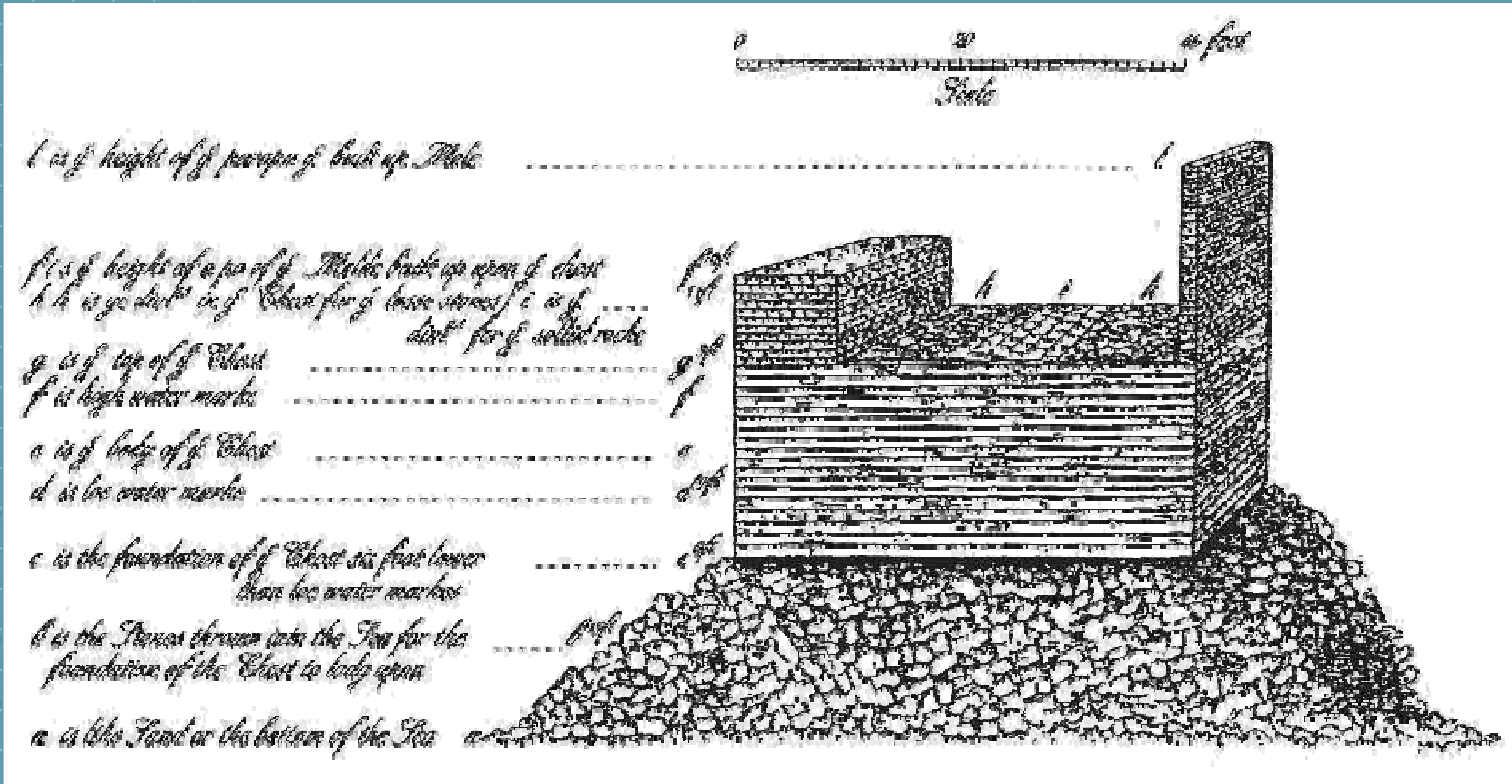
Routh EMG (1912) Tangier: England's lost Atlantic outpost, 1661-1684, John Murray, London. (Chapter 17: The Mole and Harbour)

Tangier breakwater, 1661-1684



Tangier, Greate Chest caissons

The revised caisson design, 1677, after Routh (1912)



Samuel Pepys' diary, Jan / Feb 1663

"The "12 January. ….So I went to the Committee, where we spent all this night attending to Sir J. Lawson's description of Tangier and the place for the Mole[1] of which he brought a very pretty draught.

[1] In April, 1663, … the charge for 1 year's work was £13,000. In March 1665, £36,000 had been spent on it. …. Colonel Norwood reported in 1668 that a breach had been made… which cost a considerable sum to repair.

6 February…where at the Solicitor Generals' I found Mr Cholmely and Creed reading to him the agreement for him to put into form about the contract for the Mole at Tangier, which is done at 13s the cubic yard, though upon my conscience not one of the Committee, besides the parties concerned, do understand what they do therin, whether they give too much or too little.

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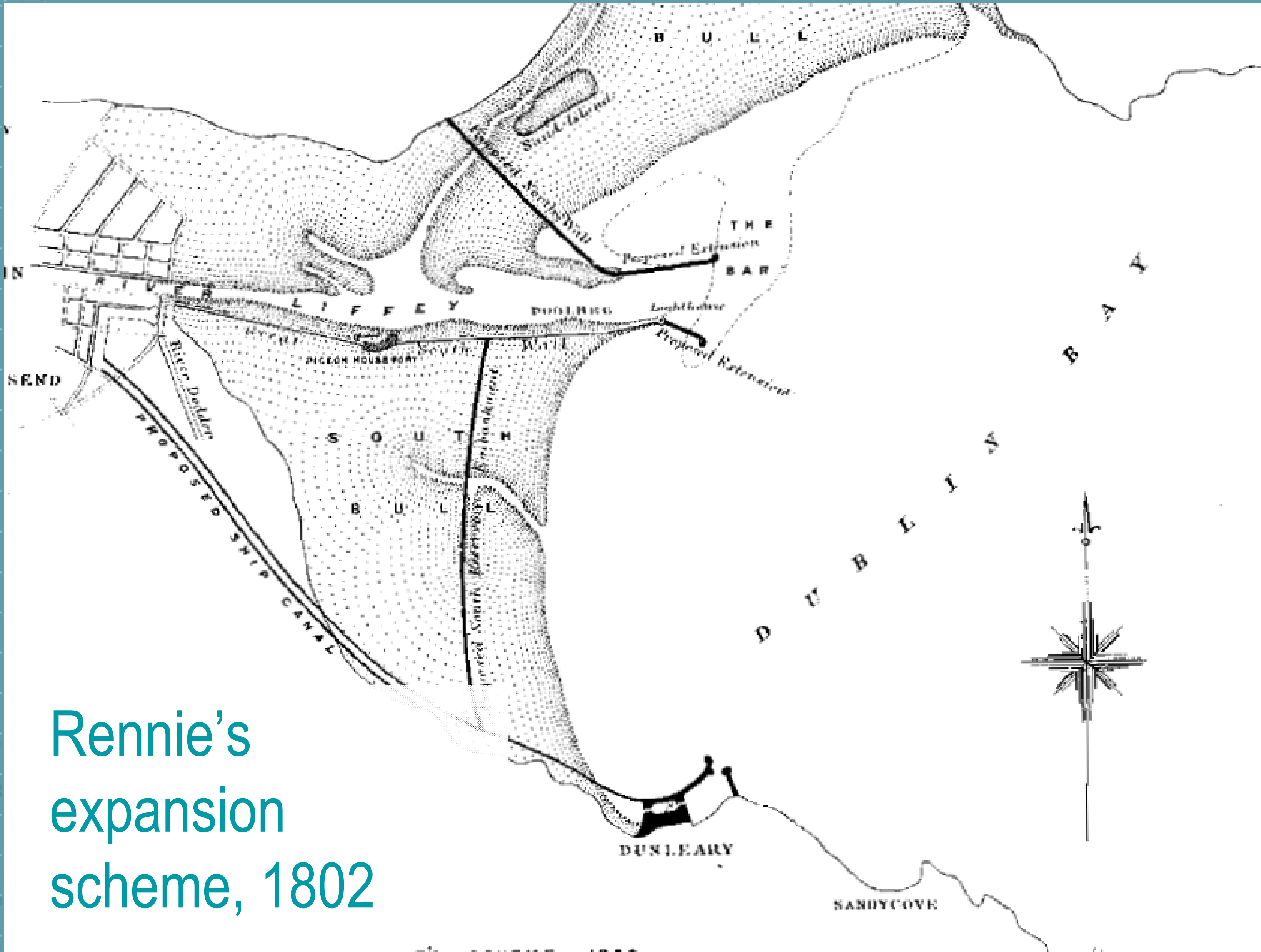
Dublin Great South Wall

Constructed 1716 – 1786
from Ringsend out to Poolbeg

Dublin Great South Wall

Dublin Great South Wall



Rennie's expansion scheme, 1802

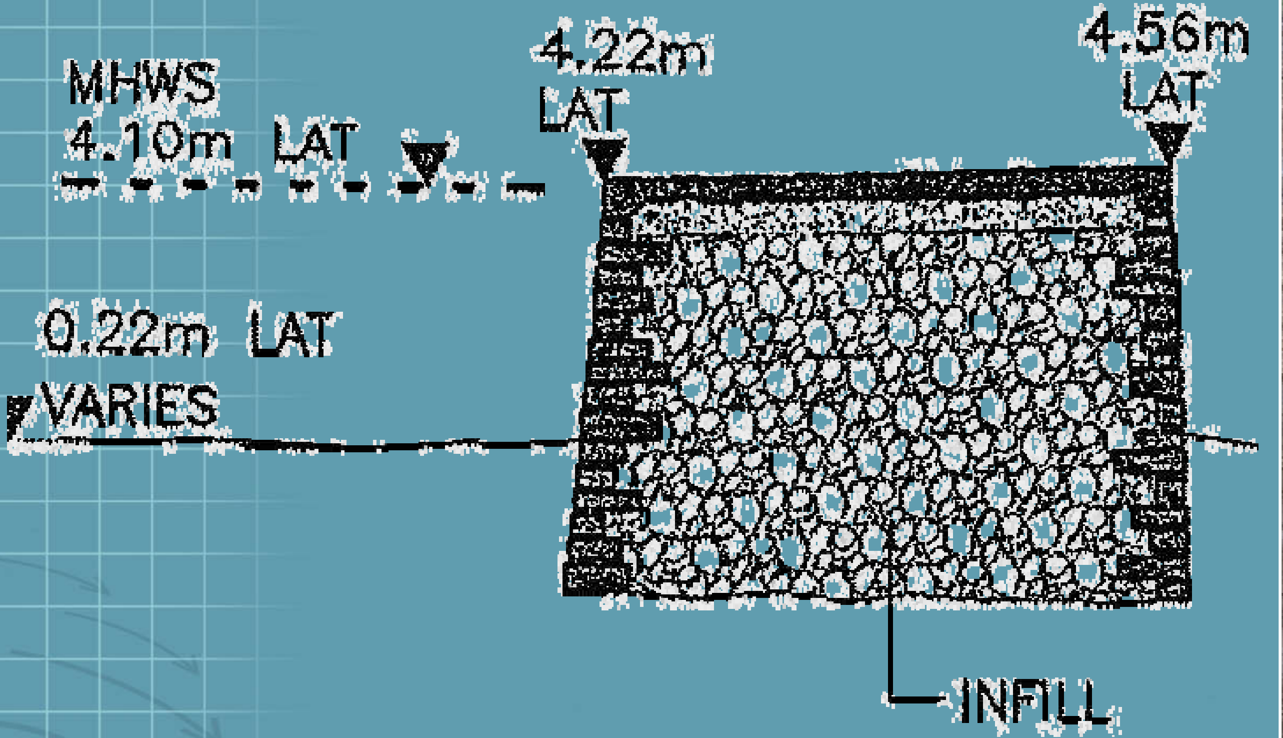
Dublin Great South Wall

High water, views from North side

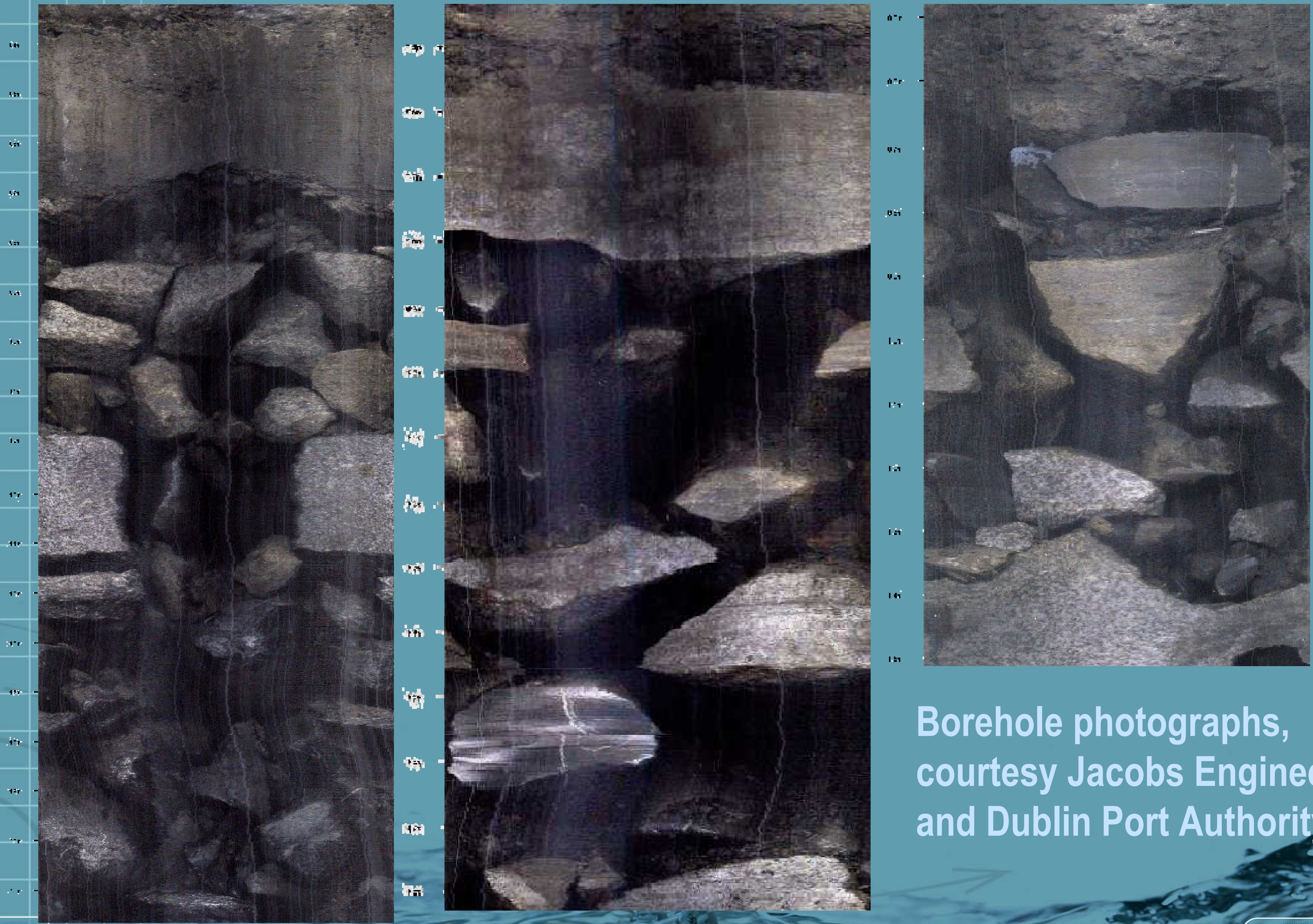
View from the South

Dublin Great South Wall

Indicative cross-section through Great South Wall

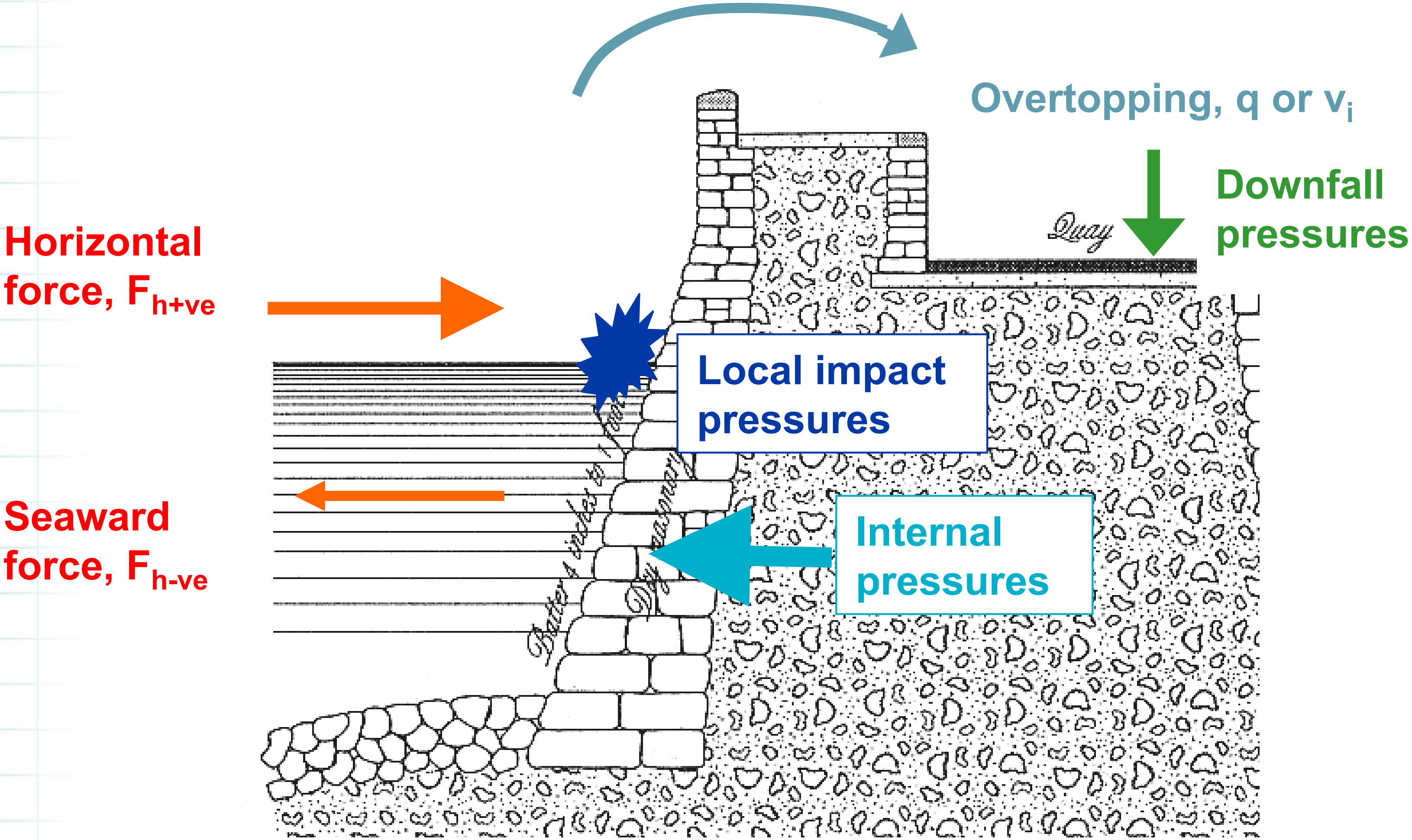


Dublin Great South Wall



Borehole photographs, courtesy Jacobs Engineering and Dublin Port Authority

Wave effects on vertical structures



Wave loads and related responses for vertical, battered or composite walls.

Wave effects on vertical structures

Impulsive wave breaking against vertical or battered walls

$\Rightarrow$ high overtopping

+ high velocities

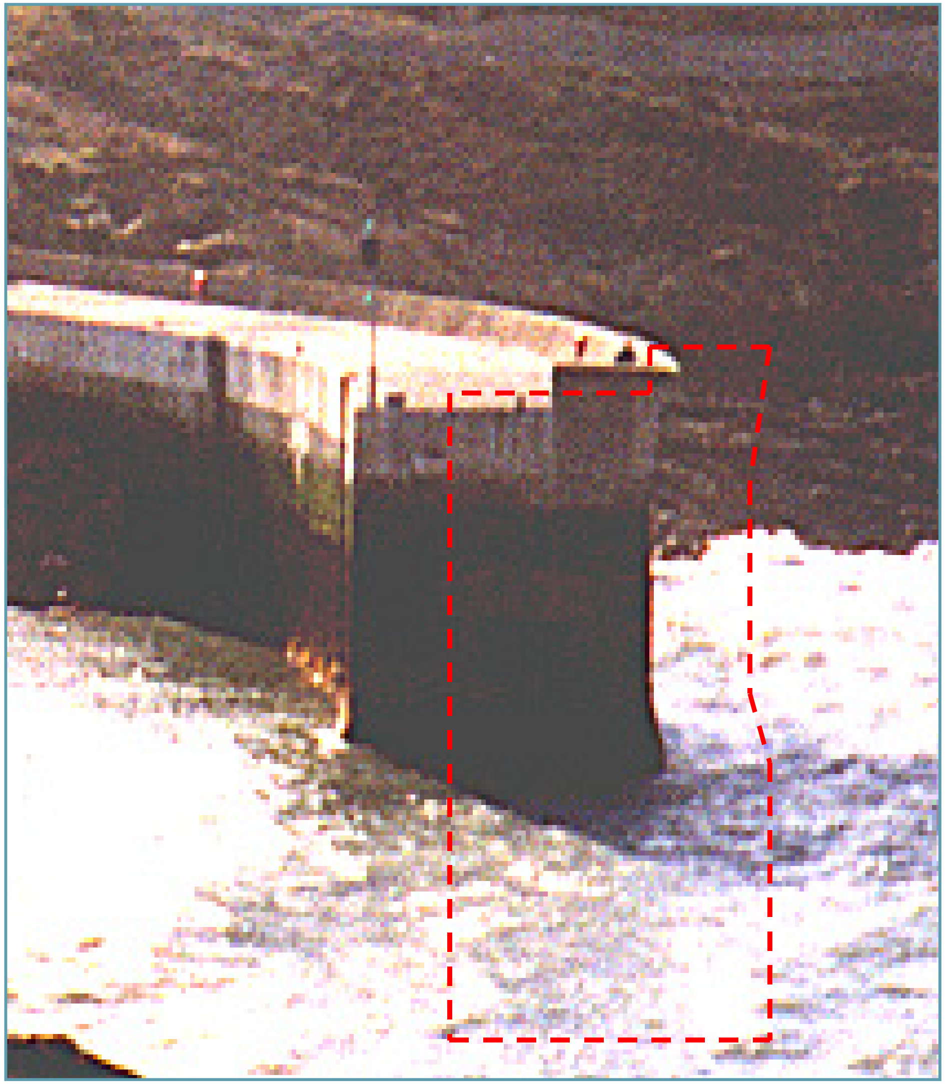
+ intense local pressures

Wave effects on vertical structures

Impulsive loads on vertical wall at Amlwch, small movements, about 1m at breakwater head.

Over-simple wave load formulae.

Ignored research on impulsive wave loadings – but so did everybody else!



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Context for determination of wave loads

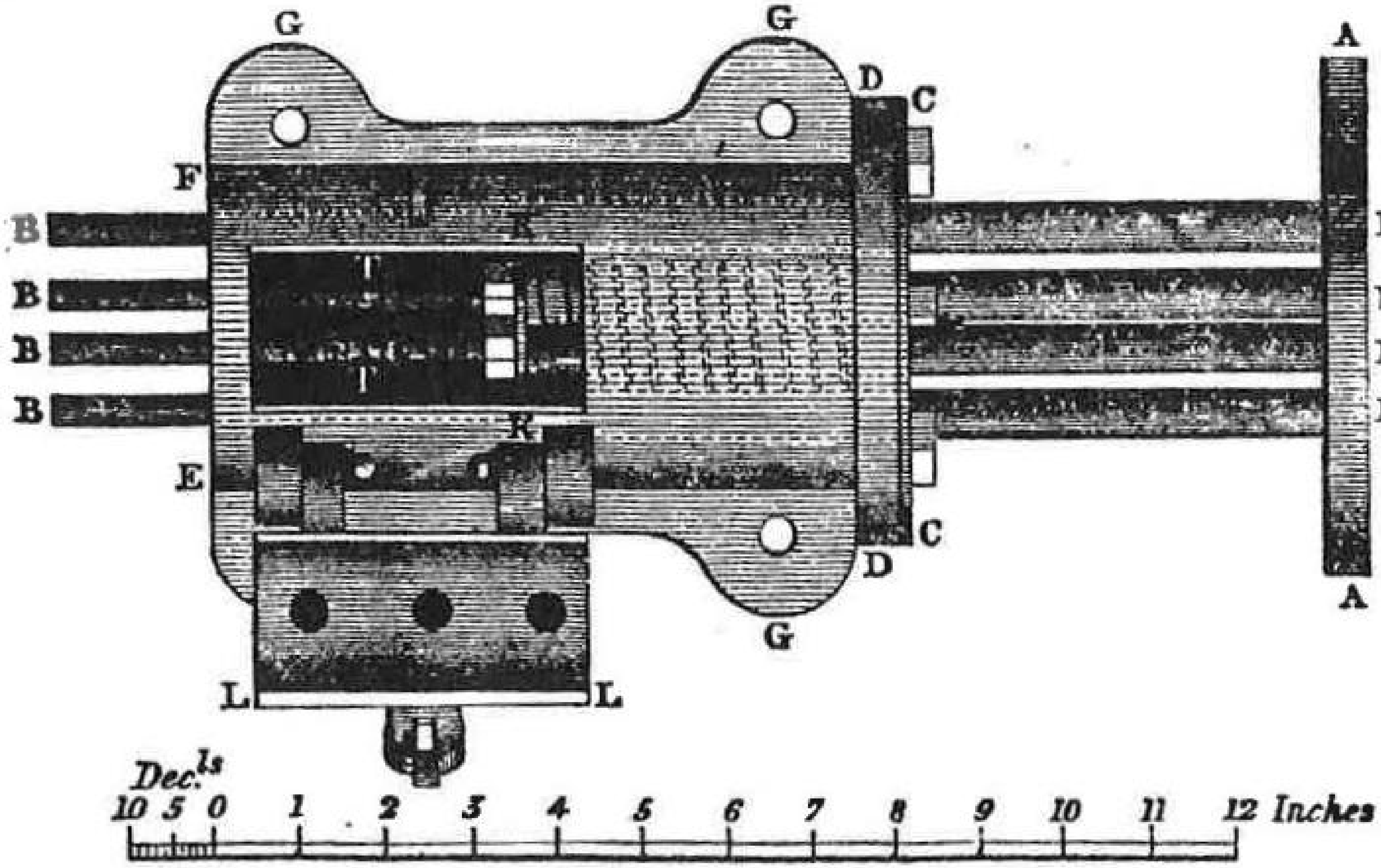
"*Perhaps it may be considered rather hard by the young engineer, that he should be left to be guided entirely by circumstances, without the aid of any one general principle for his assistance.*"

Scott Russell J.(1847) *On the practical forms of breakwaters, sea walls and other engineering works exposed to the action of waves*, Proc. ICE, Vol VI, pp135-148.

"*In forming designs of marine works, the engineer has always a difficulty in estimating the force of the waves with which he has to contend….. The information … derived from local informants … is not satisfactory. I shall explain the construction of this simple self-registering instrument*…"

Stevenson T. (1849) *Account of experiments upon the force of the waves of the Atlantic and German oceans*, Proc. ICE, pp23-32 (reported by David Stevenson)

Wave effects on vertical structures

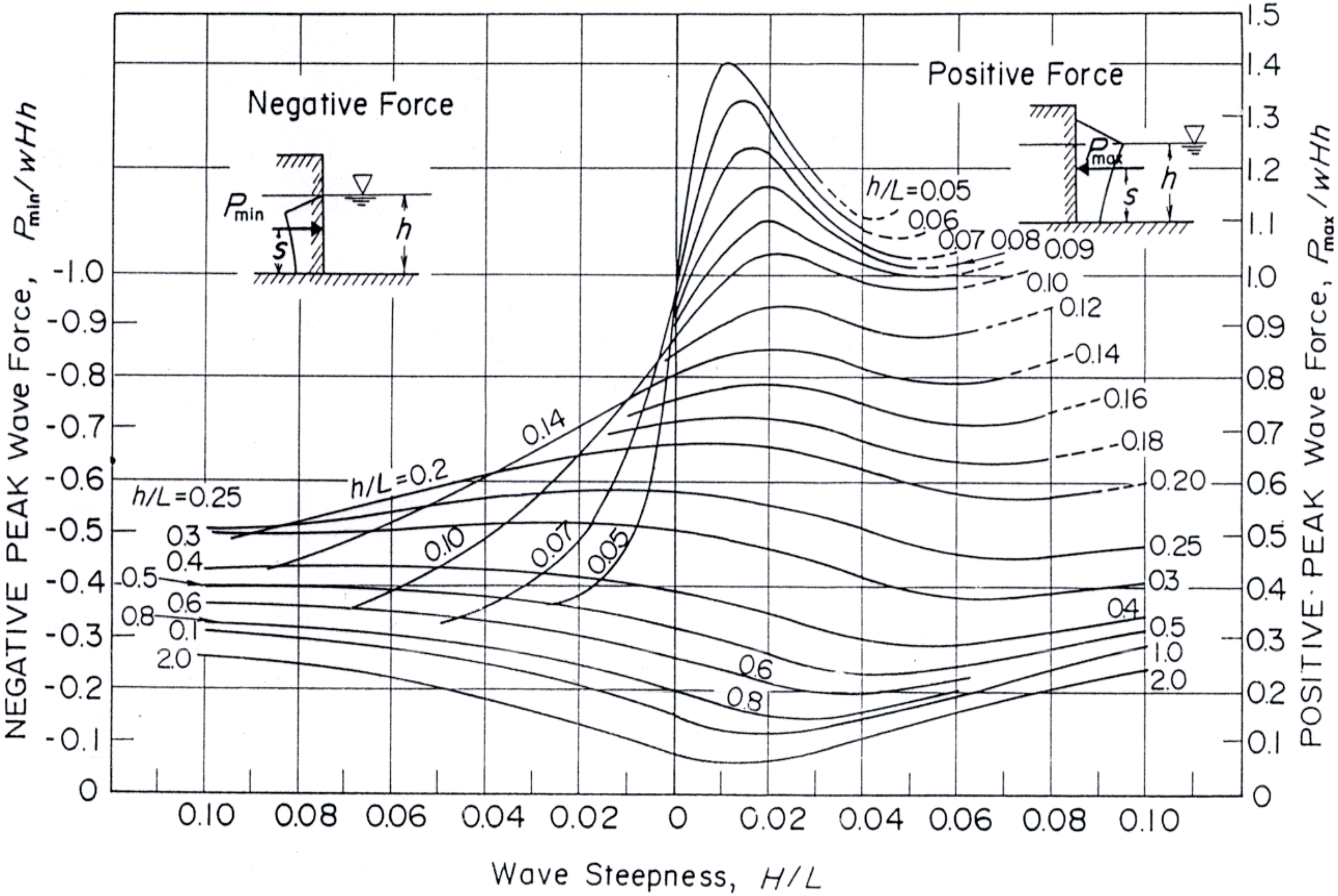


Stephenson's wave force Dynamometer, circa 1845

Wave load and overtopping analysis methods, 1967 - 2010

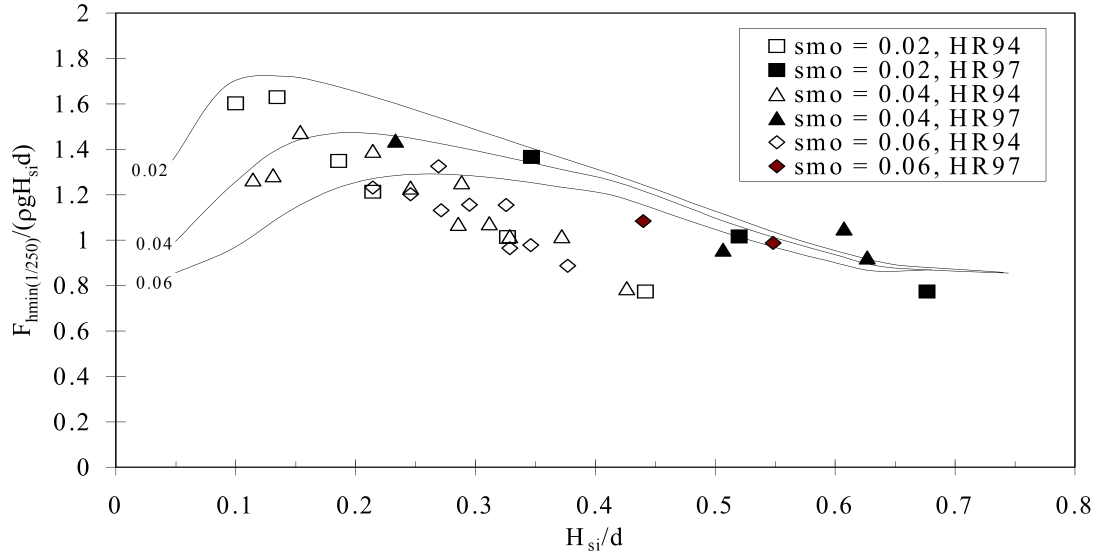
Quasi-static or non-impulsive loads, Goda

Wave loads +ve and -ve (graphical method), Goda (1967) and empirical methods Goda (1985, 2000)

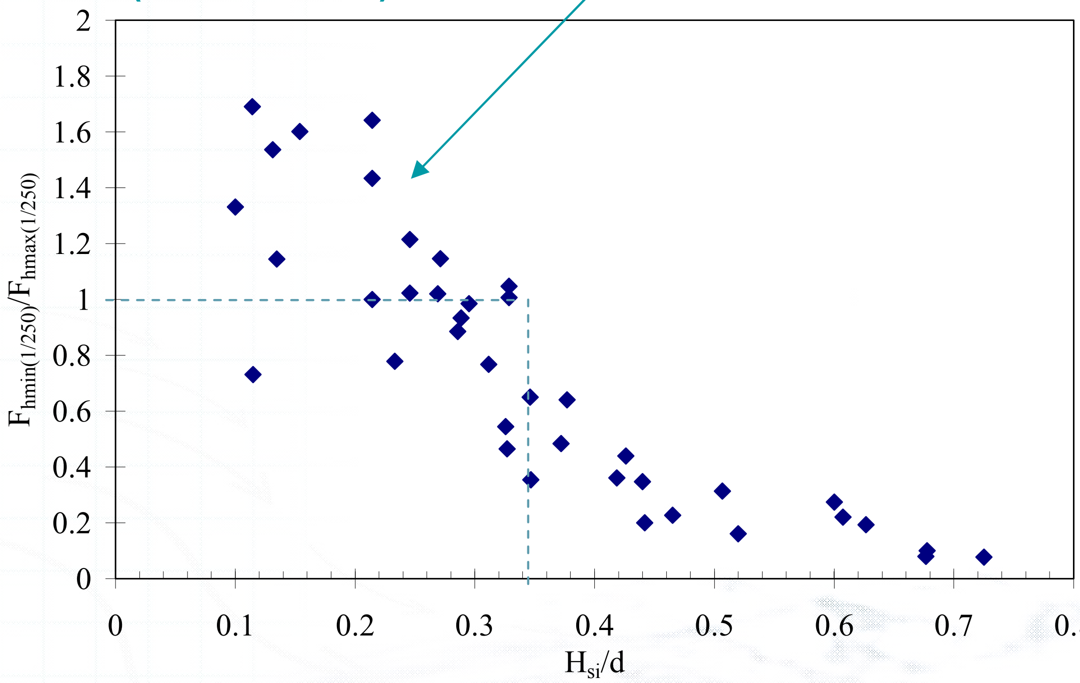


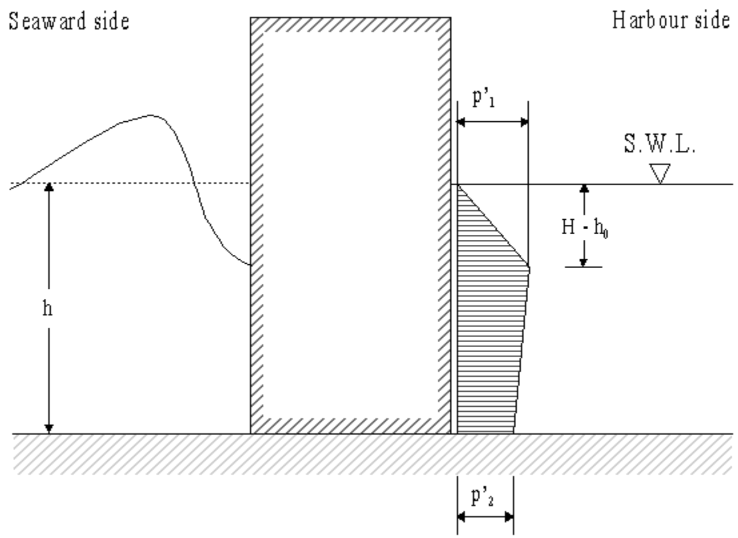
Seaward wave loads - vertical walls

Guidance on seaward loads from McConnell et al (1999)



Negative forces exceed positive (landward) forces



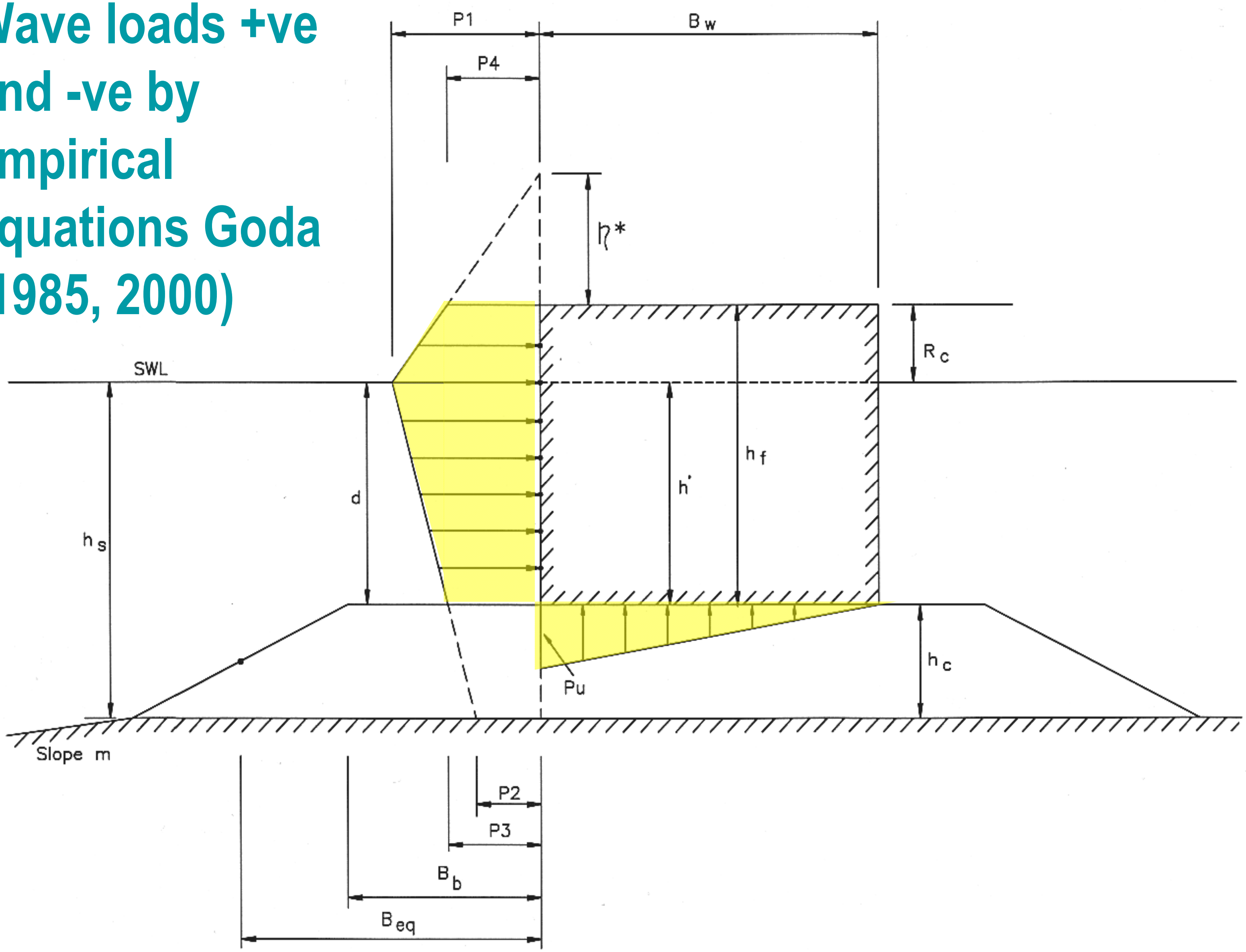


Sainflou formula: $p'_1 = \rho g (H - h_0)$ $h_0 = (\pi H^2/L) \coth (2\pi h/L)$

$p'_2 = \rho g H / \{\cosh (2\pi h/L)\}$

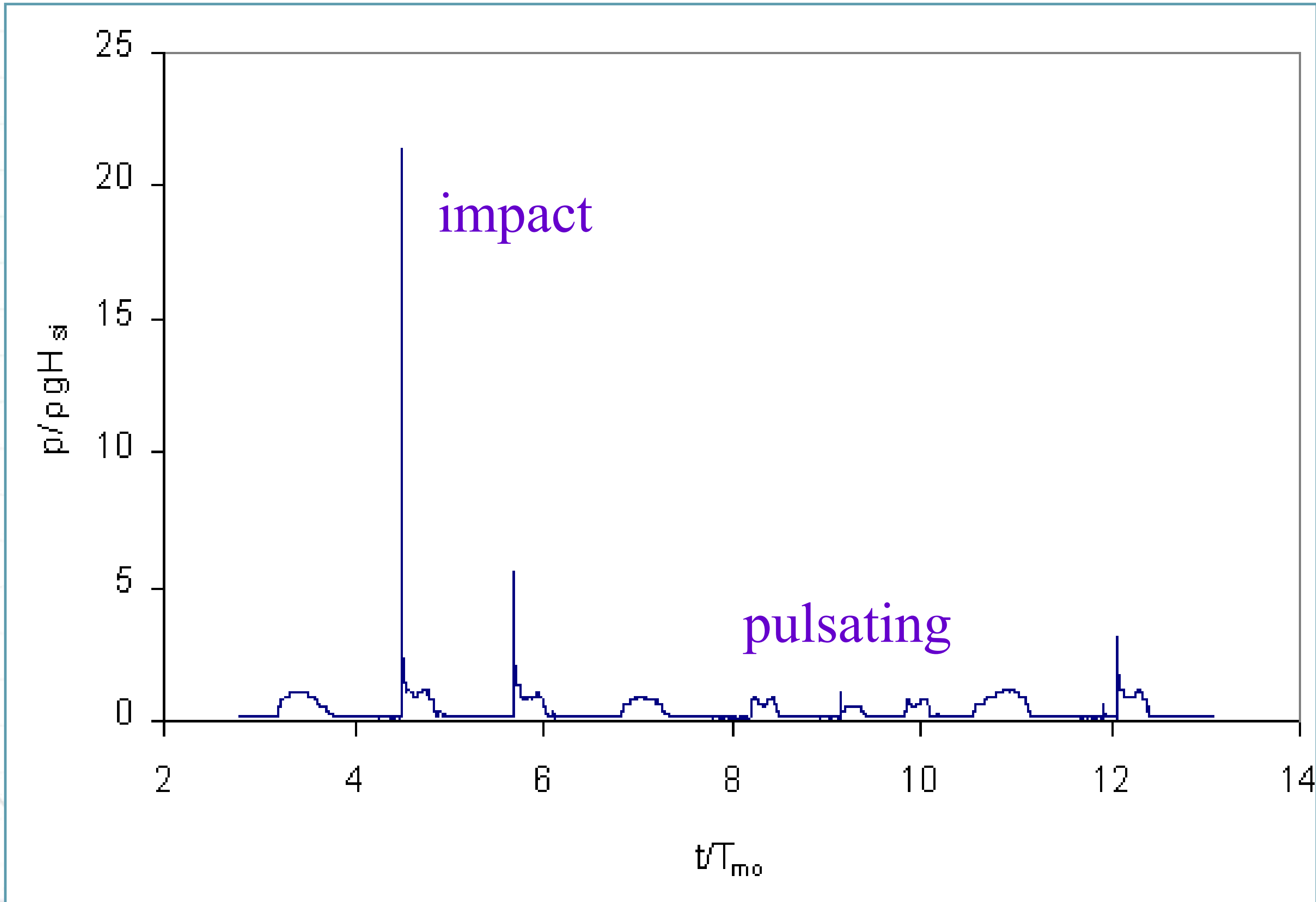
Quasi-static or non-impulsive loads, Goda

Wave loads +ve and -ve by empirical equations Goda (1985, 2000)



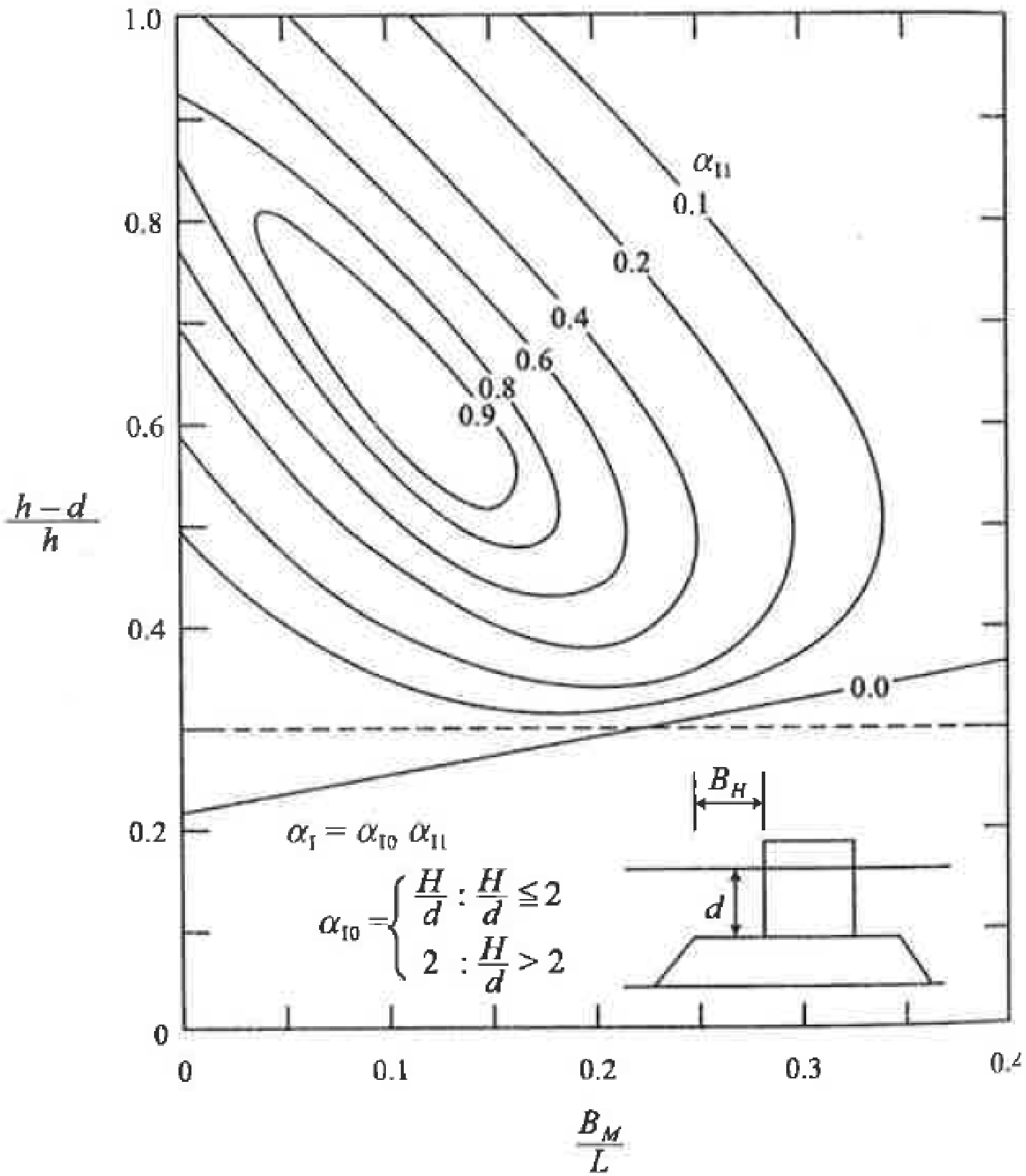
Wave effects on vertical structures

Pulsating and impulsive wave loads, from McKenna (1995), Allsop et al (1996)



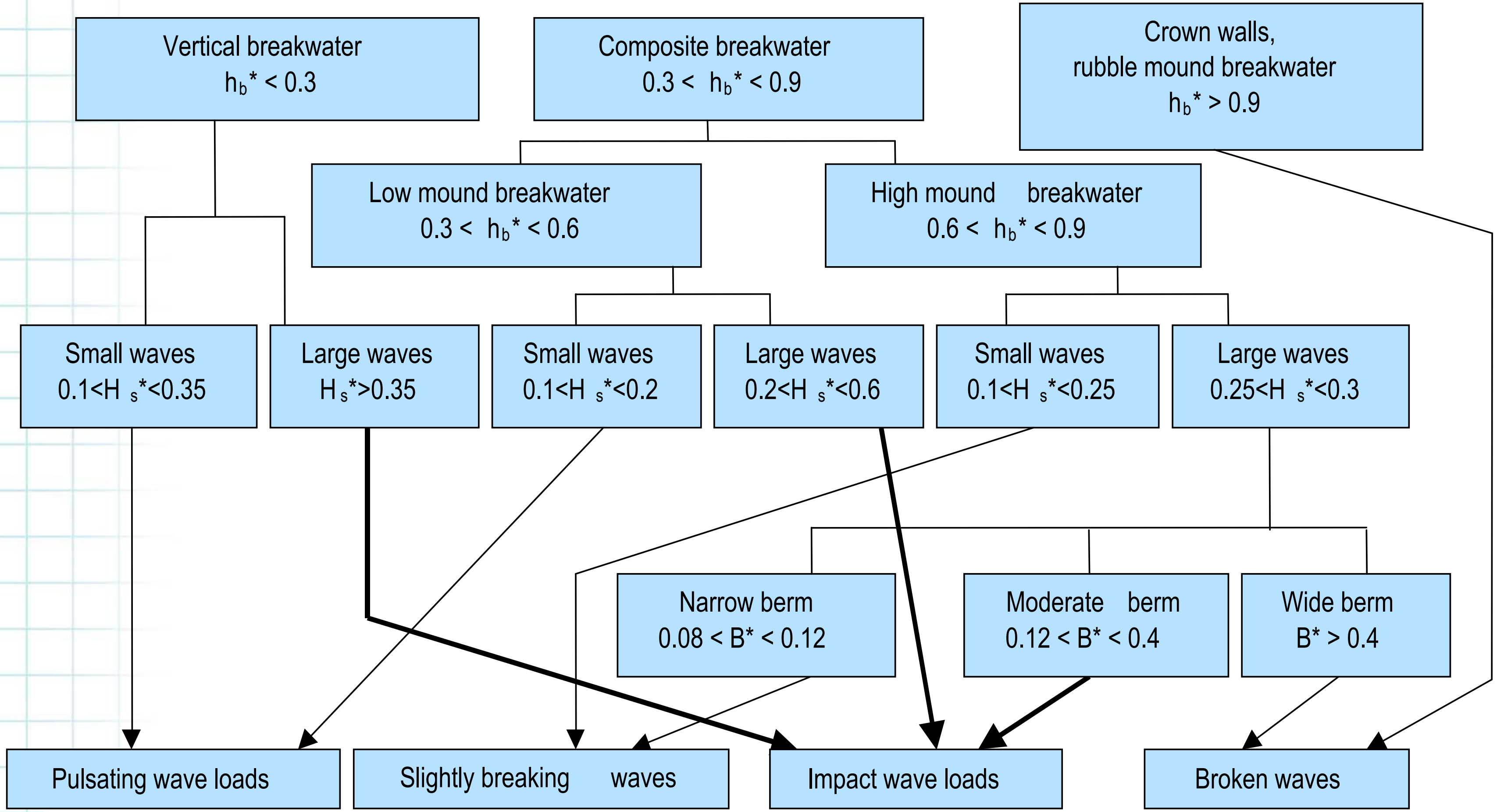
Impulsive loads, Takahashi

Takahashi's impulsive breaking wave pressure coefficient, α_{I1}, applied to Goda's formulae to enhan[c]
α_I. Takes values of α_I between 0 and 2.

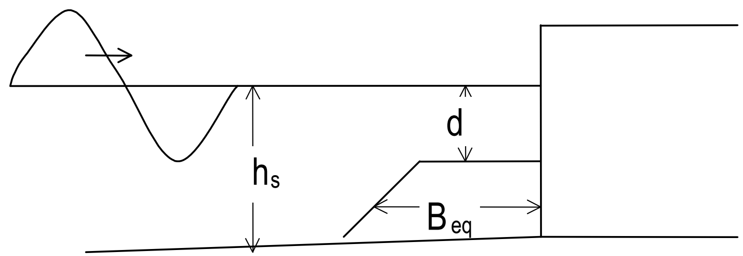


Takahashi S. Tanimoto K. & Shimosako (1992) *Experimental study of impulsive pressures on composite breakwaters* Report of Port & Harbour Research Insti[tute] Vol 31, No 5, pp 35-74, PHRI, Yokosuka.

Types of wave loads (PROVERBS)

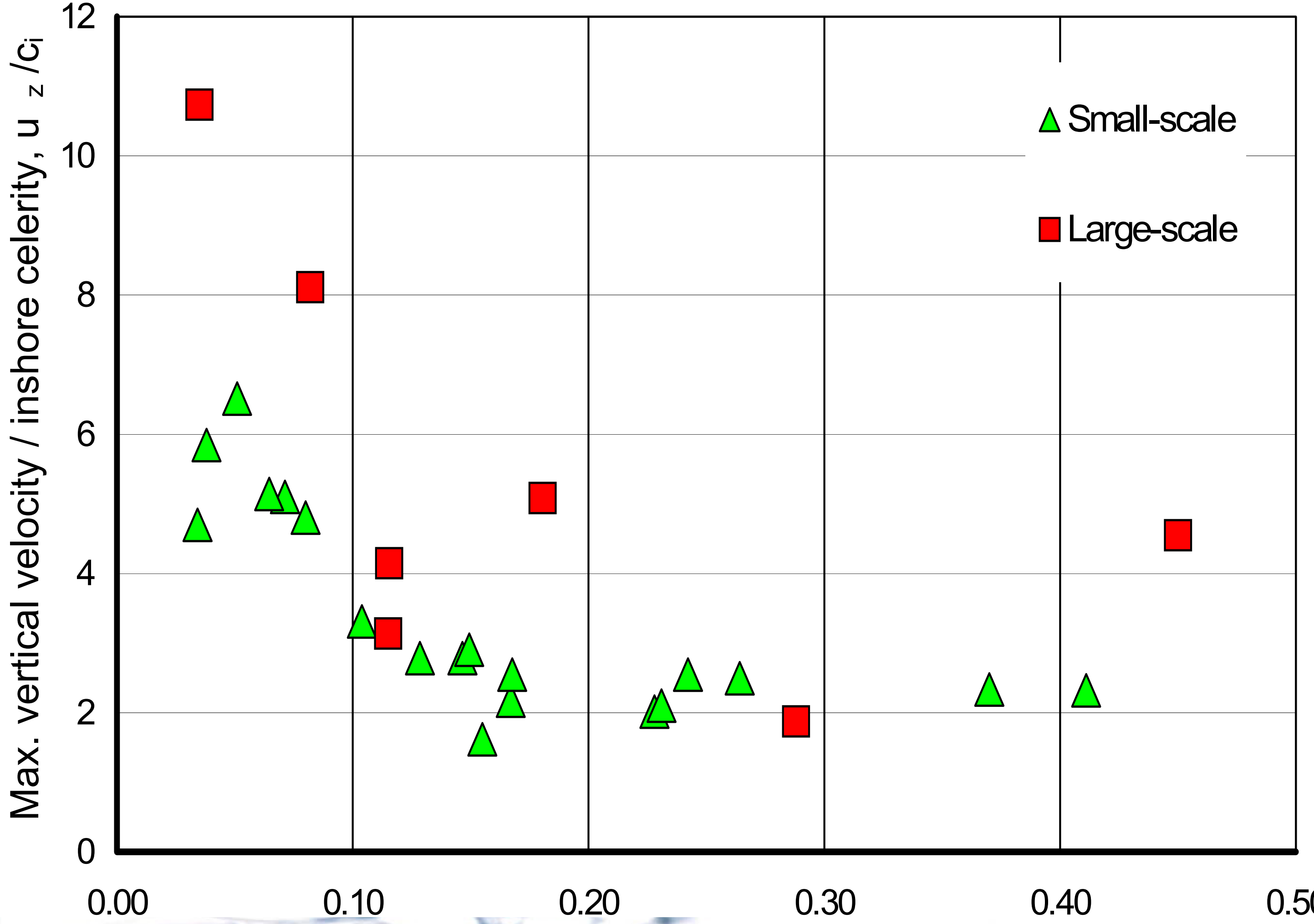


Dimensionless parameters :
relative mound height, $h_b^* = h_b/h_s$;
relative wave height, $H_s^* = H_{si}/h_s$;
relative berm width, $B^* = B_{eq}/L_{pi}$;



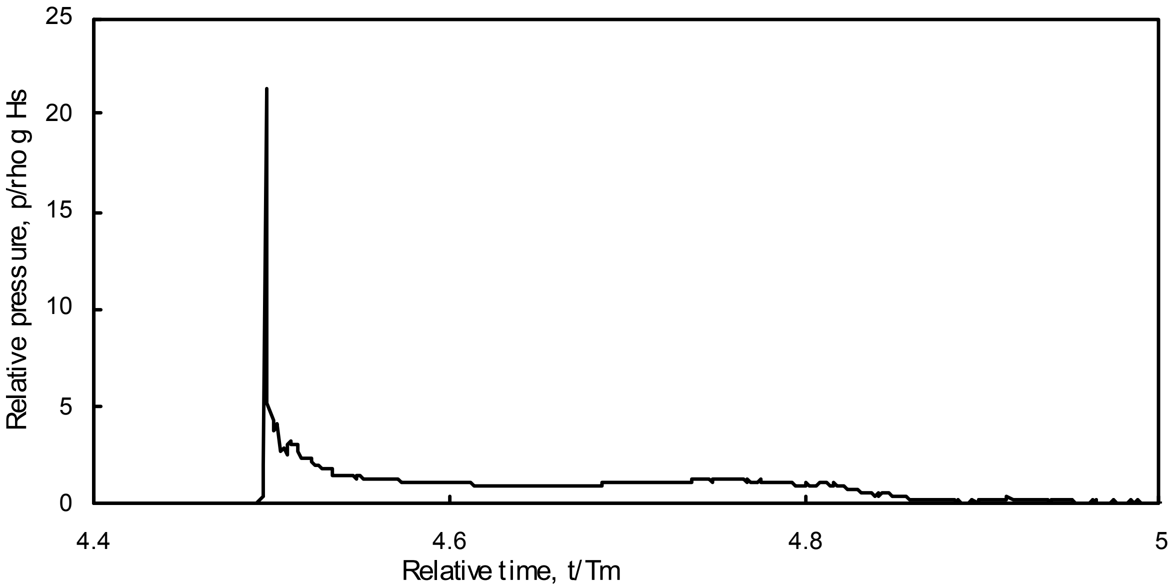
Overtopping processes at vertical walls

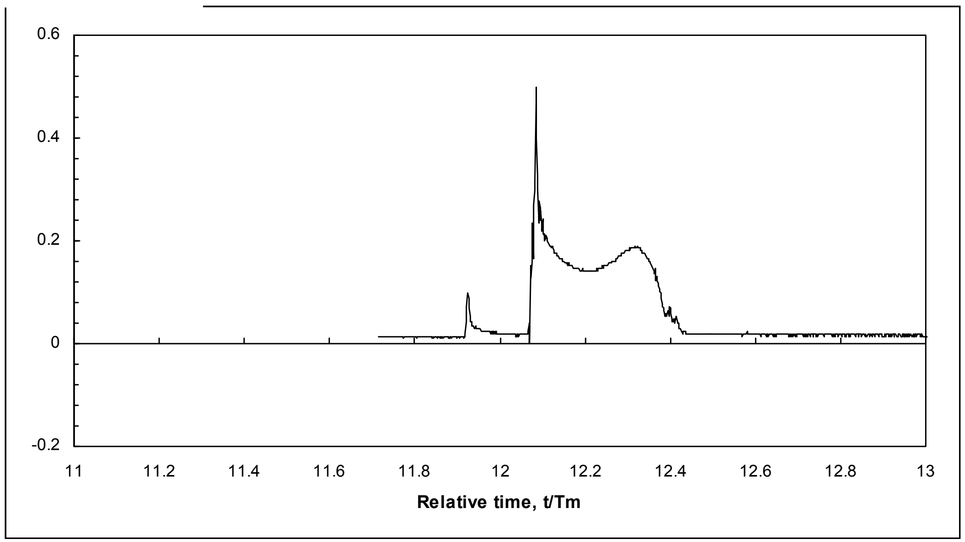
Overtopping velocities at vertical walls –from VOWS and Big-VOWS tests at Edinburgh and UPC, see: Allsop et al (2005) proc. ICE, Mar Eng.



$$h^* = (h/H_s)(2\pi h/gT_m^2)$$

Impulsive wave loads - vertical walls





Impulsive wave loads from McKenna (1997) PhD tests at Wallingford, see also Allsop et al (1996).

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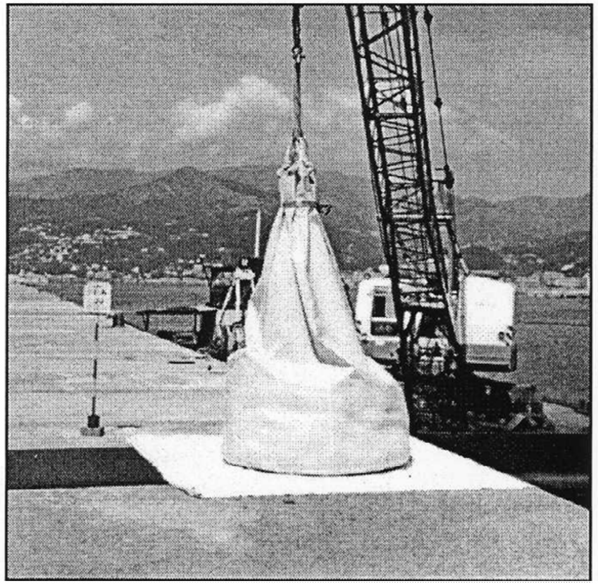
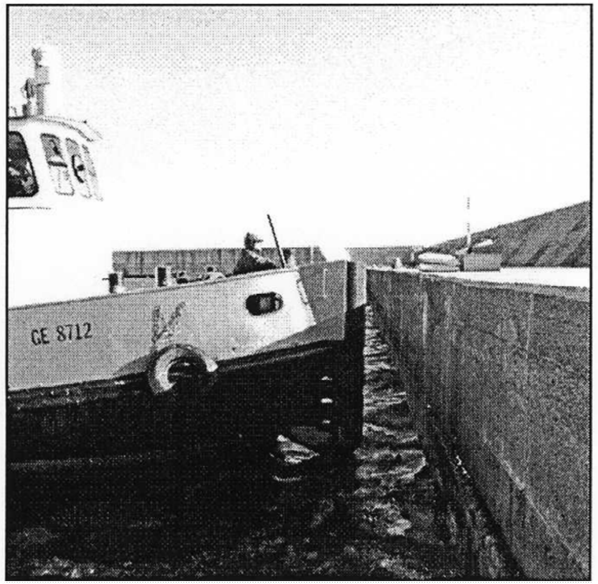
Measurements of dynamic responses

PROVERBS – Lamberti et al (1999), Vol IIb, Ch 3

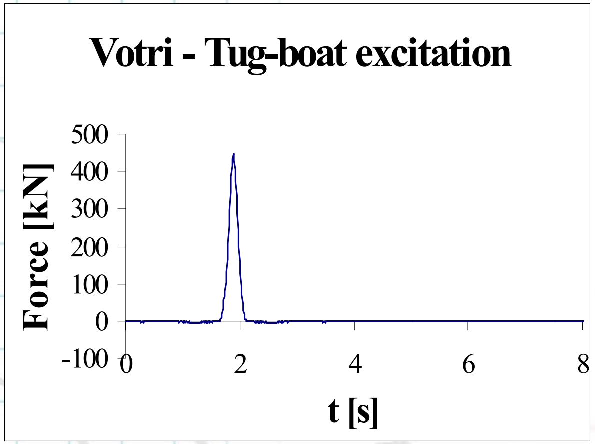
Motions of the caisson measured by 15 accelerometers



2t sandbag dropped from 5 m



100 tonne tugboat



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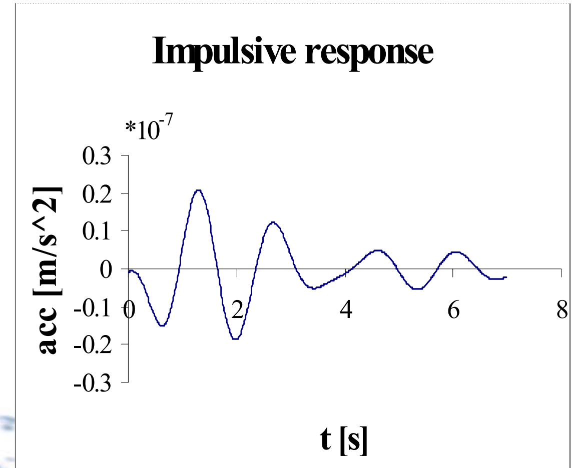
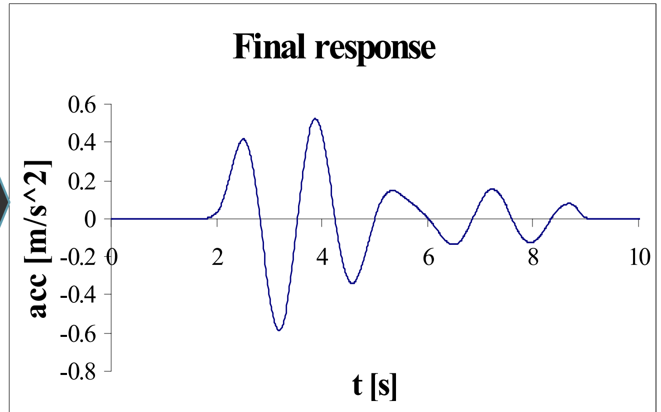
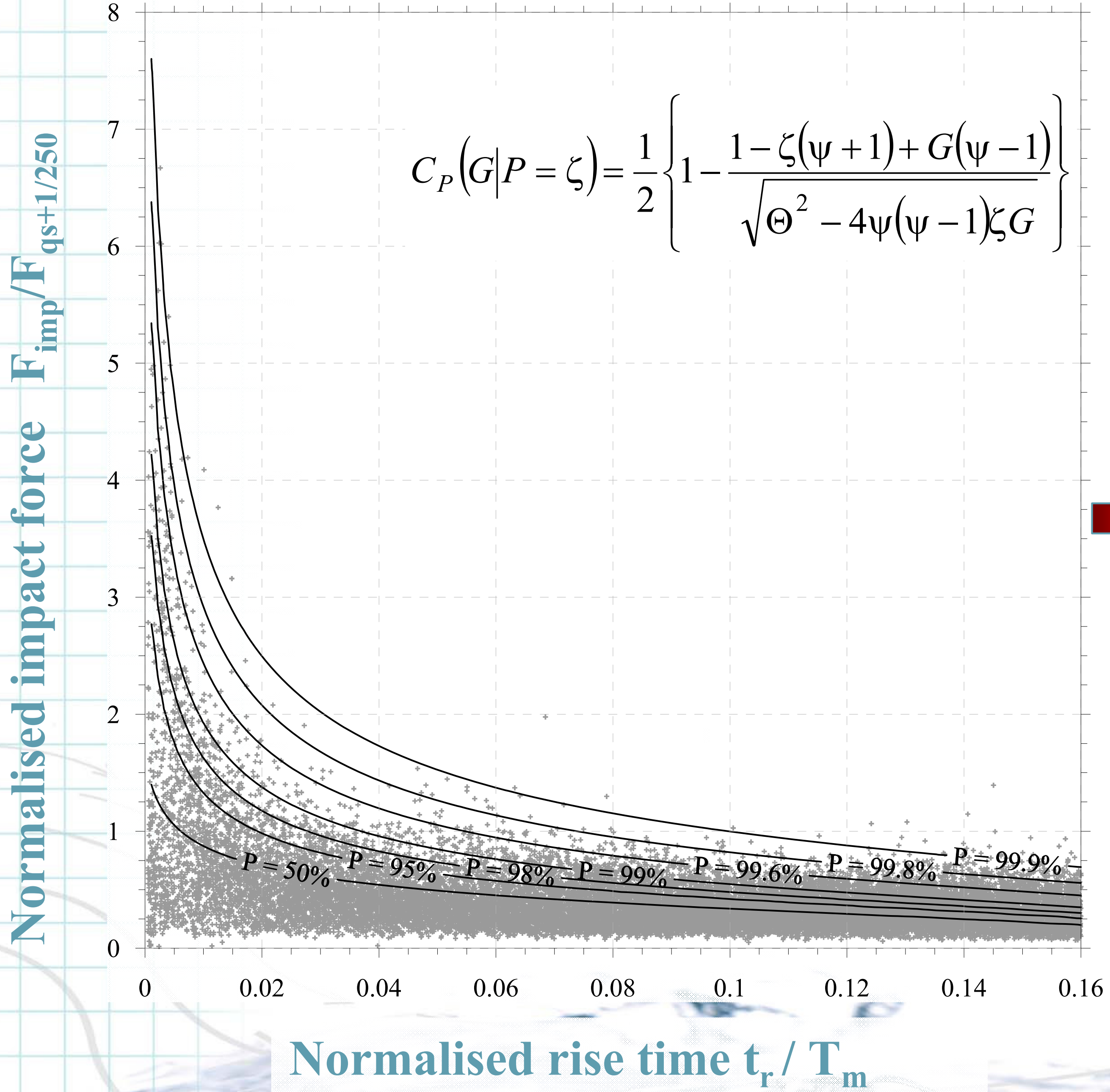
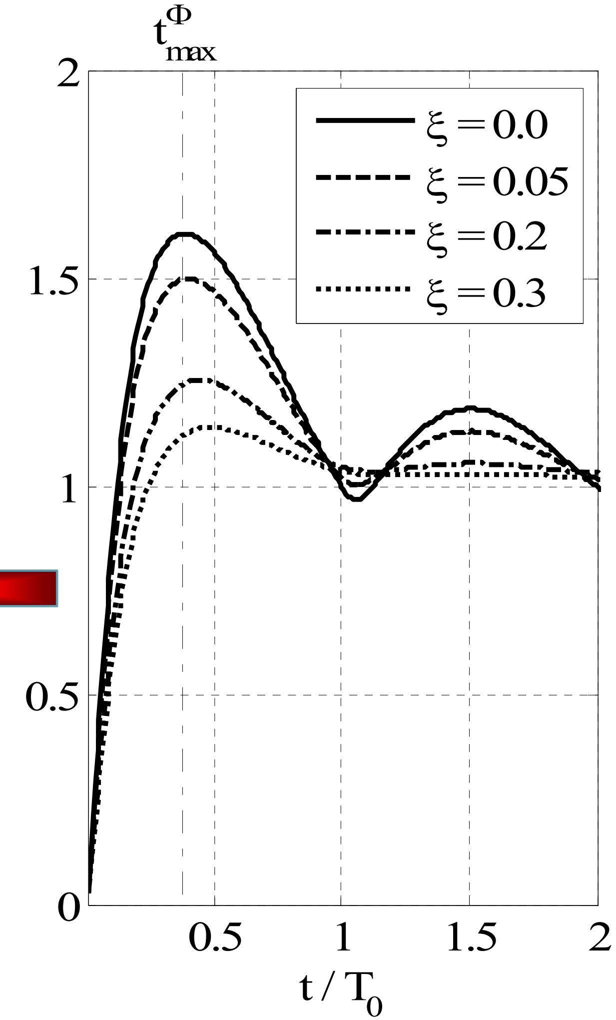




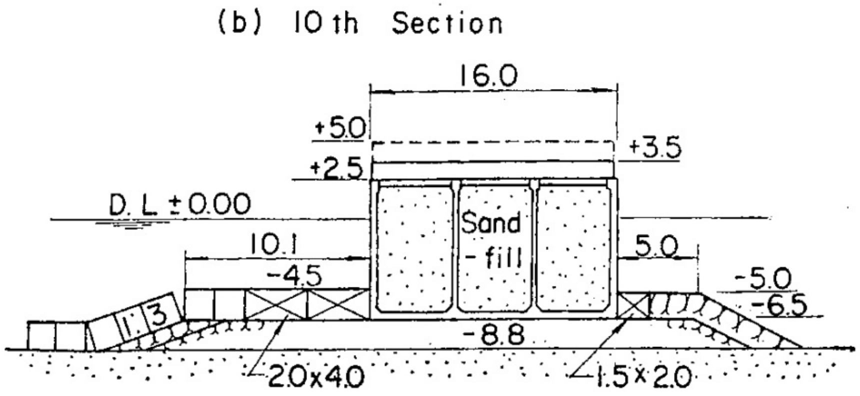
Impulsive wave loads - vertical walls





Dynamic response of a SDOF to **pulse** excitation

Impulsive wave loads - vertical walls



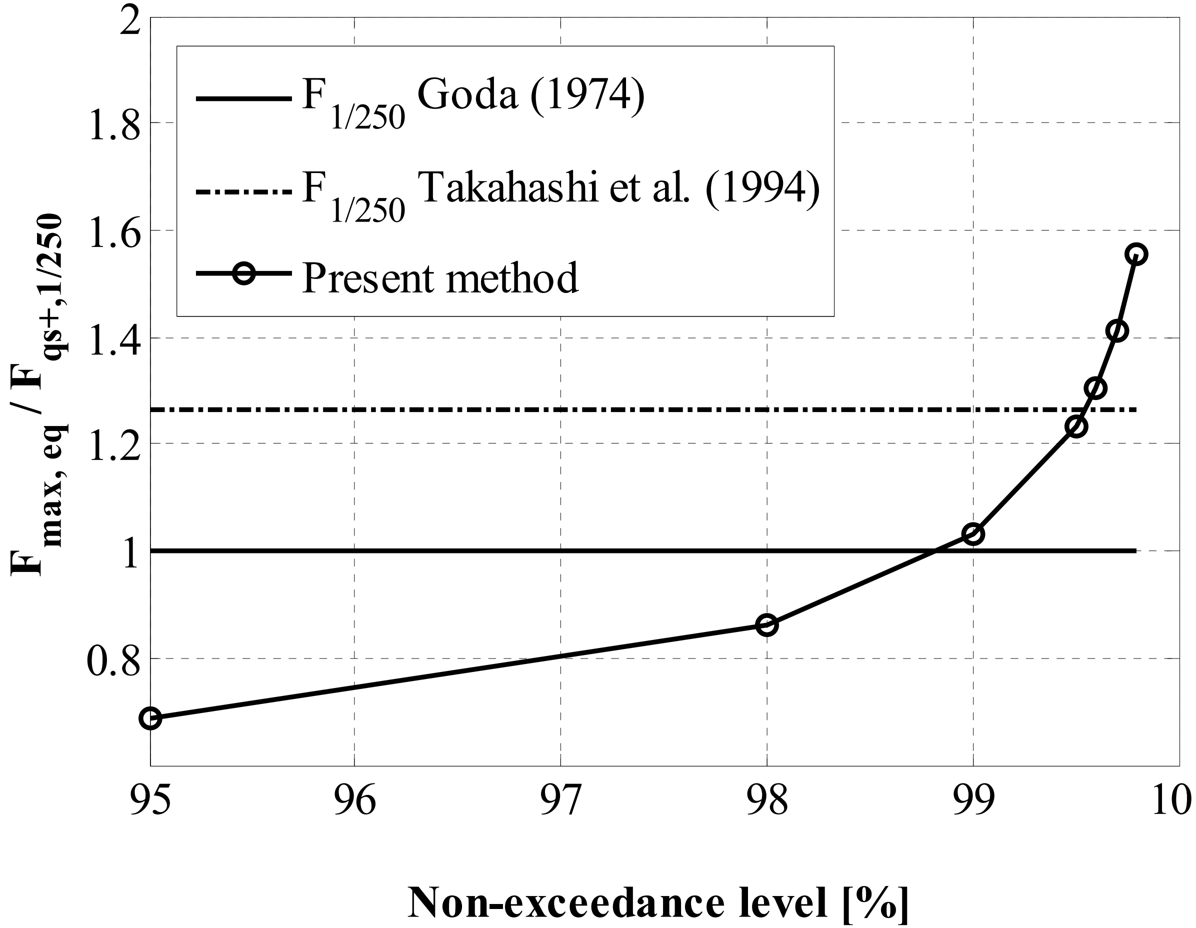


Illustration of use of extended method after Piscopia et al (2007, 2010) predicting impulsive loads of one of Goda's test cases, see Goda (1975, 1985).

Piscopia R, Cuomo G, & Allsop W (2007) *Evaluation of design impact loads based on joint probability of impact maxima and rise times*, Proc. Conf Coastal Structures 2007, publn Corila / ASCE

Permeabilities of blockwork and fill

a) open / permeable, k = high, constant (approx.)

b) grouted / sealed, k = low, constant (approx.)

c1) open both faces, gradual internal permeabilities

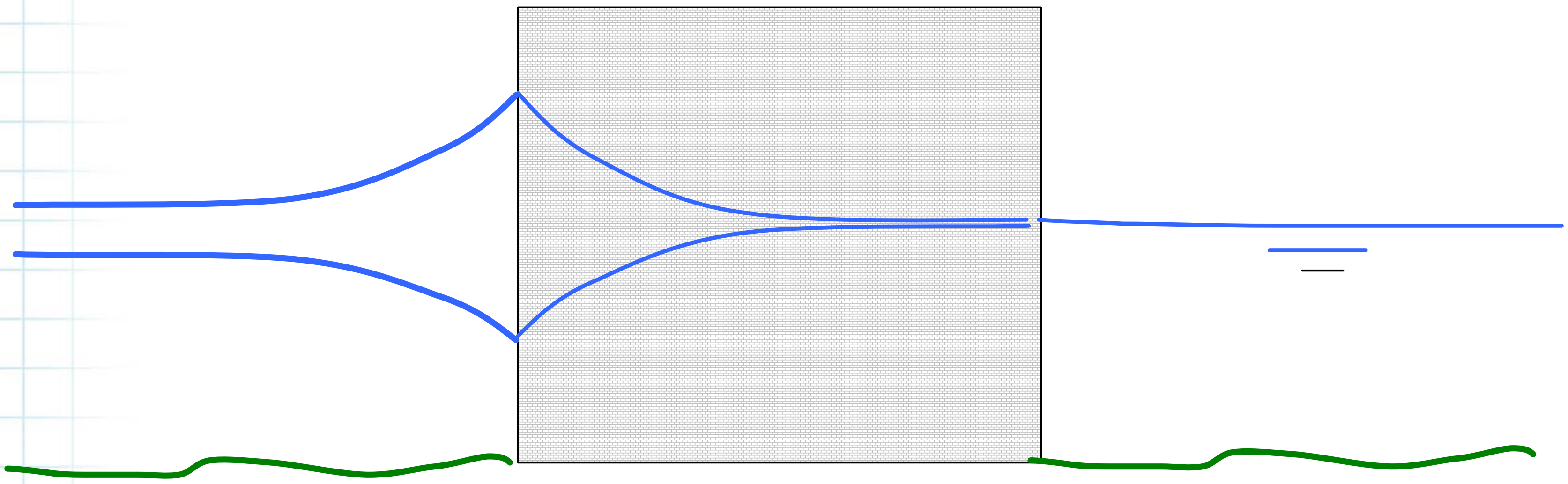
c2) closed front face, stepped permeability gradients

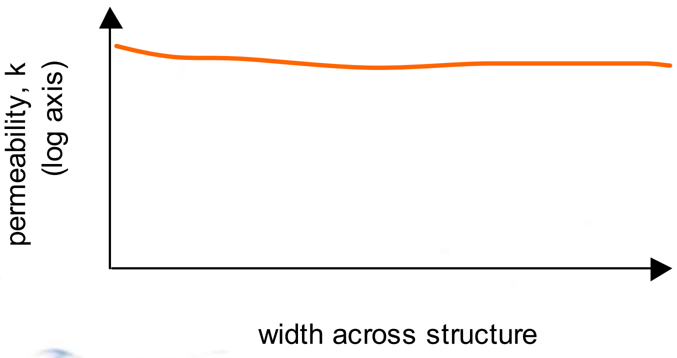
c3) closed both faces, stepped permeability gradients

Bruce T, Allsop N.W.H., Cooker M., Franco L. & Müller G.U., (2000) *How safe are blockwork breakwaters and seawalls against wave attack*, Proc. 27th ICCE, publn. ASCE, New York.

Permeabilities of blockwork and fill

a) open / permeable, k = high and constant (approx.)

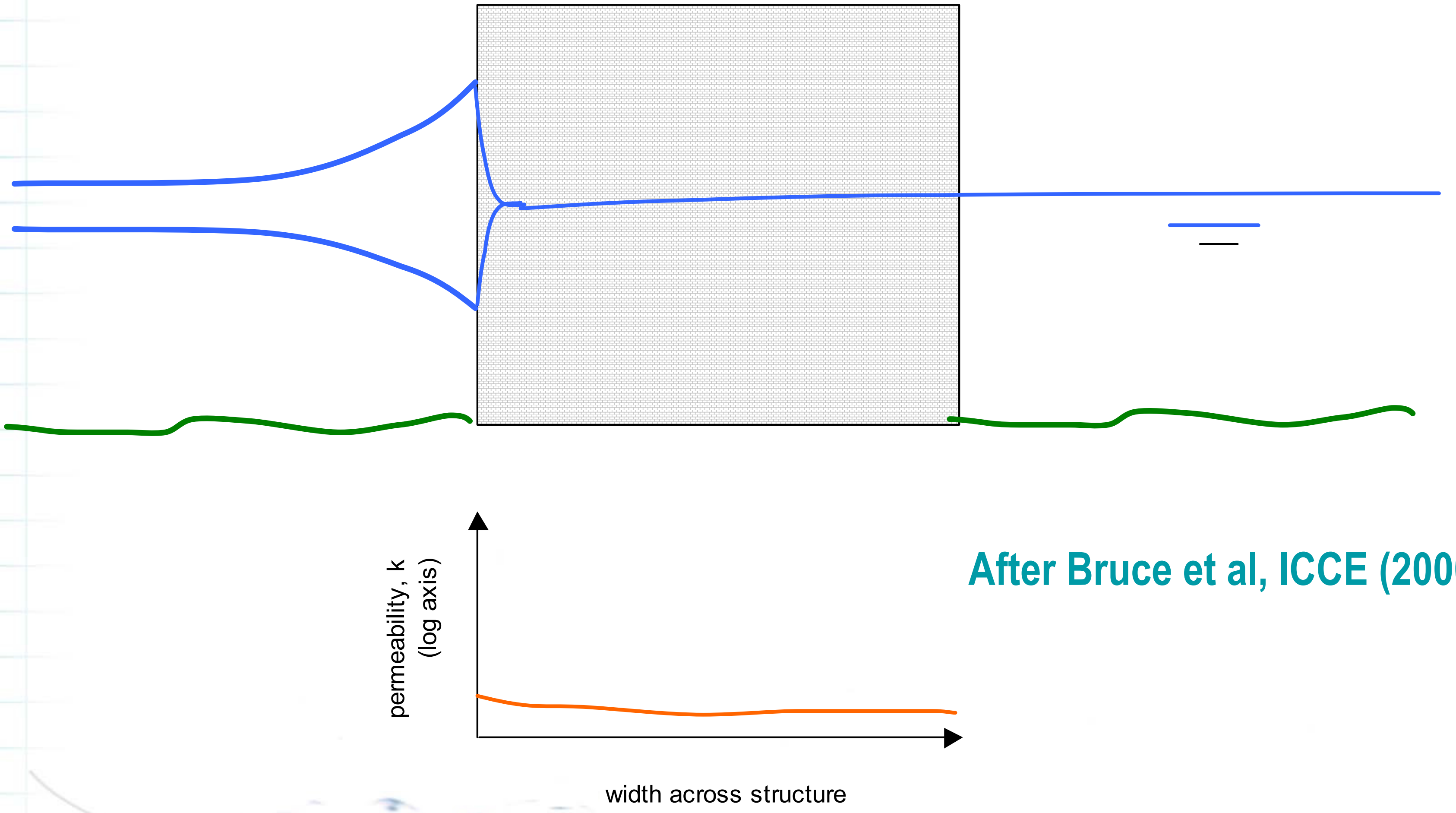




After Bruce et al, ICCE (2000)

Permeabilities of blockwork and fill

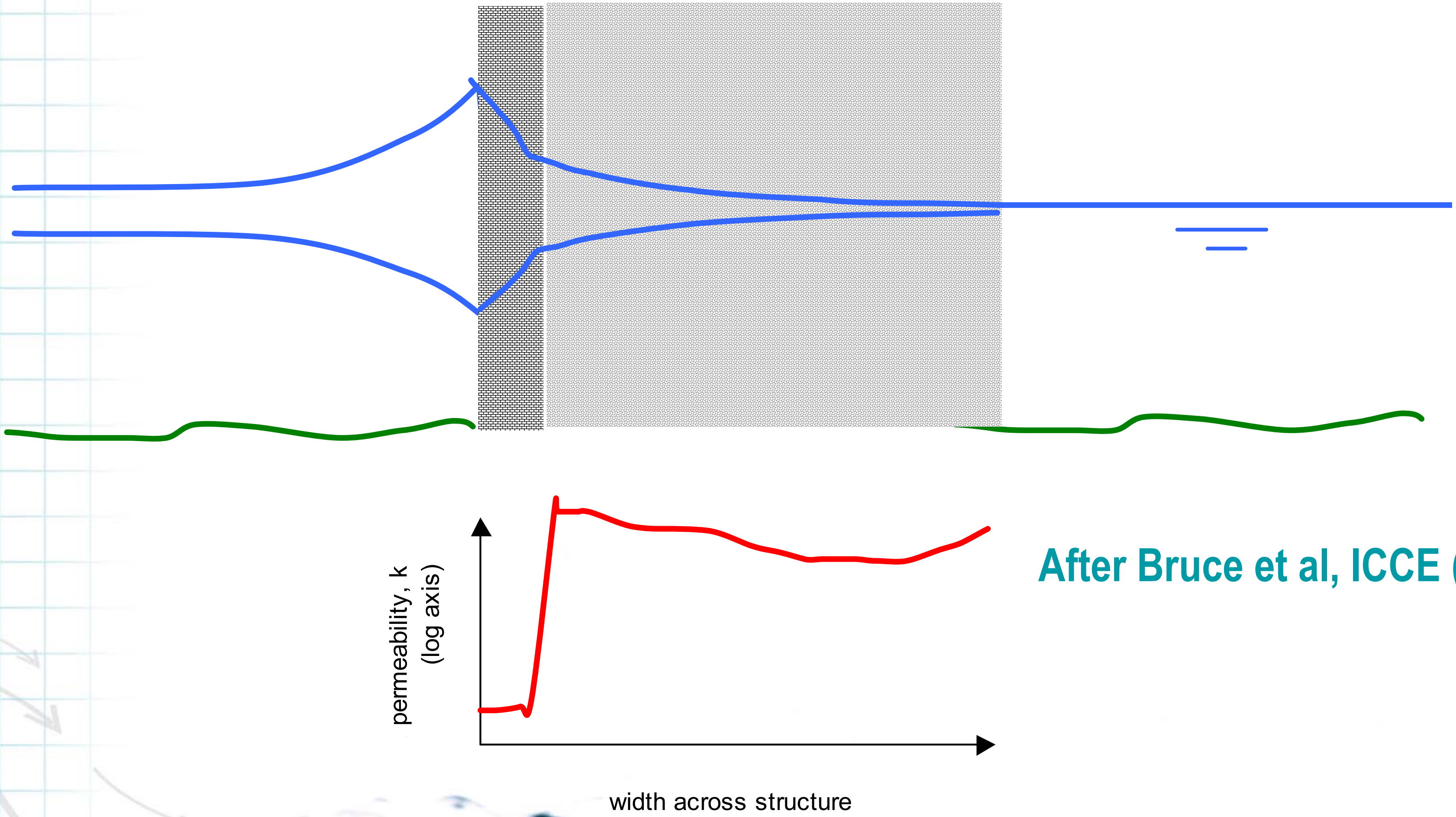
b) grouted / sealed, k = low, constant (approx.)



After Bruce et al, ICCE (2000)

Permeabilities of blockwork and fill

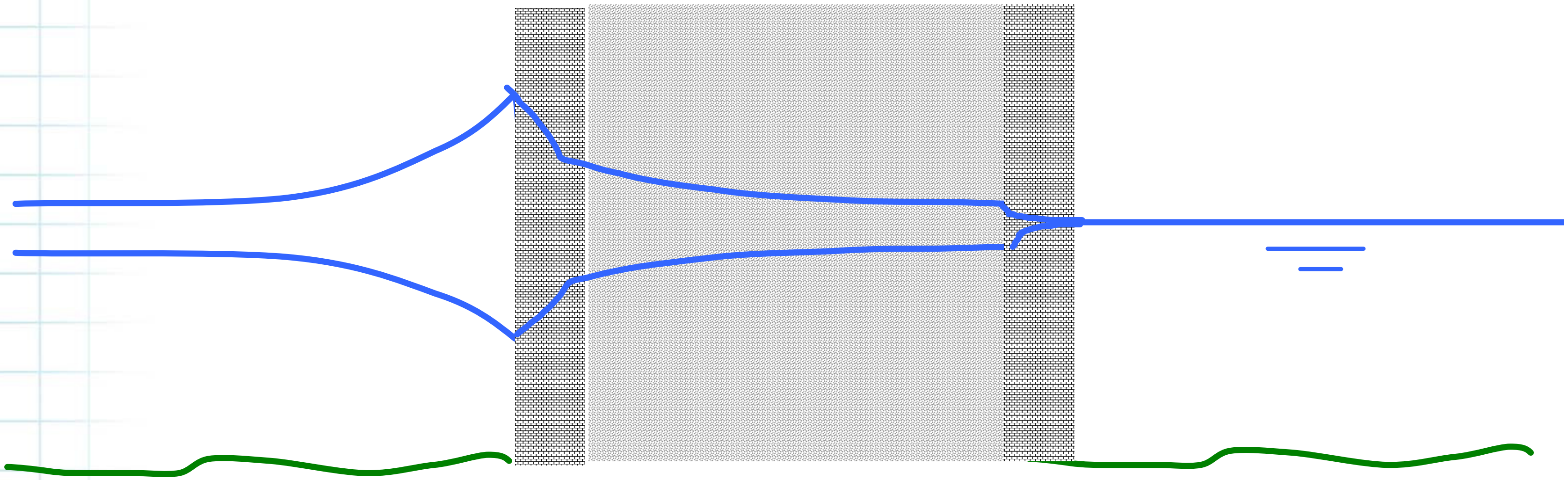
c2) stepped permeability gradients, closed front face

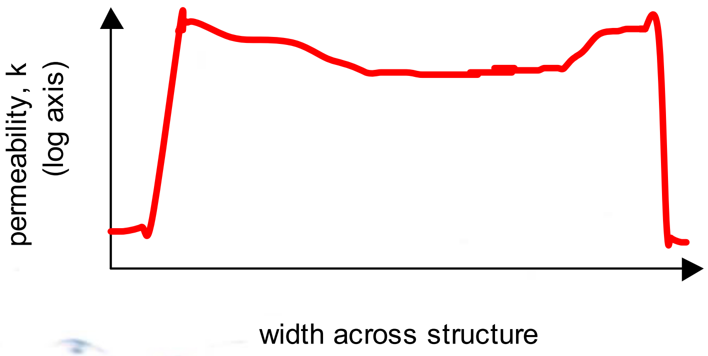


After Bruce et al, ICCE (2000)

Permeabilities of blockwork and fill

c3) stepped permeability gradients, closed both faces





After Bruce et al, ICCE (2000)

Port Logan – blockwork failure

Port Logan, Rhinns of Galloway. Failure of close fitting blockwork armour (low permeability) over ungrouted rock fill.

Wave loads on vertical structures

Movement under impulsive waves of blocks within a blockwork wall by Muller et al (2003), Marth et al (2004).

[Photos courtesy Dr Gerald Muller, Univ. Southampton.]

Marth R., Muller G., Klavzar A., Wolters G., Allsop W., & Bruce T. (2004) *Analysis of blockwork coastal structures* Proc. 29th ICCE, Lisbon.

Wave loads on vertical structures

Stress flow within a blockwork wall simulating load transfer from a parapet wall onto a battered face, studies by Muller et al (2002).

[Photo courtesy Dr Gerald Muller, University of Southampton.]

Müller G., Allsop N.W.H., Bruce T., Cooker M., Hull P., & Franco L. (2002) *Wave effects on blockwork structures: model tests* IAHR Jo. Hydr. Res., Vol. 40.

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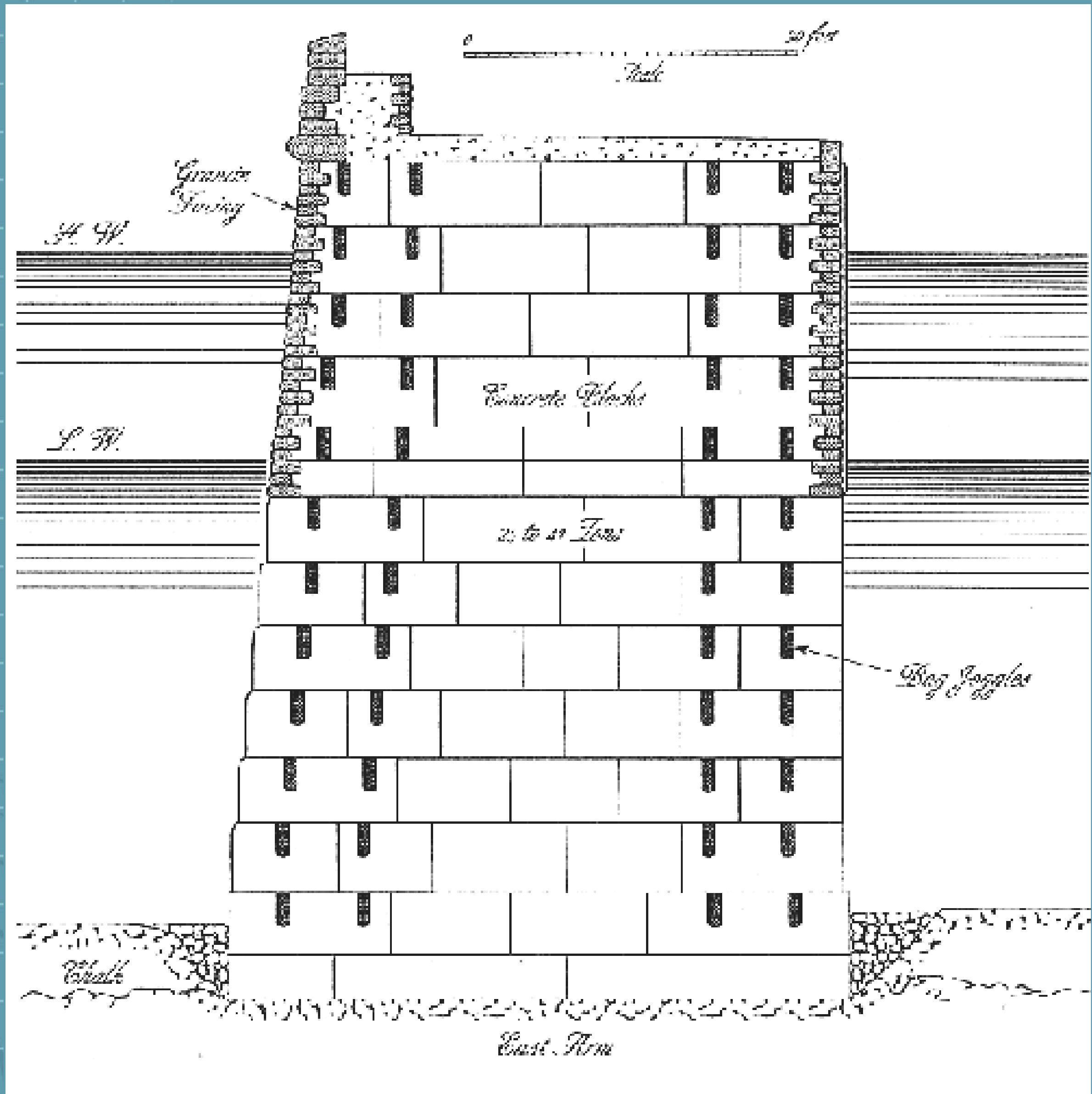
Dover Breakwaters (Admiralty and Western)

1880-1900

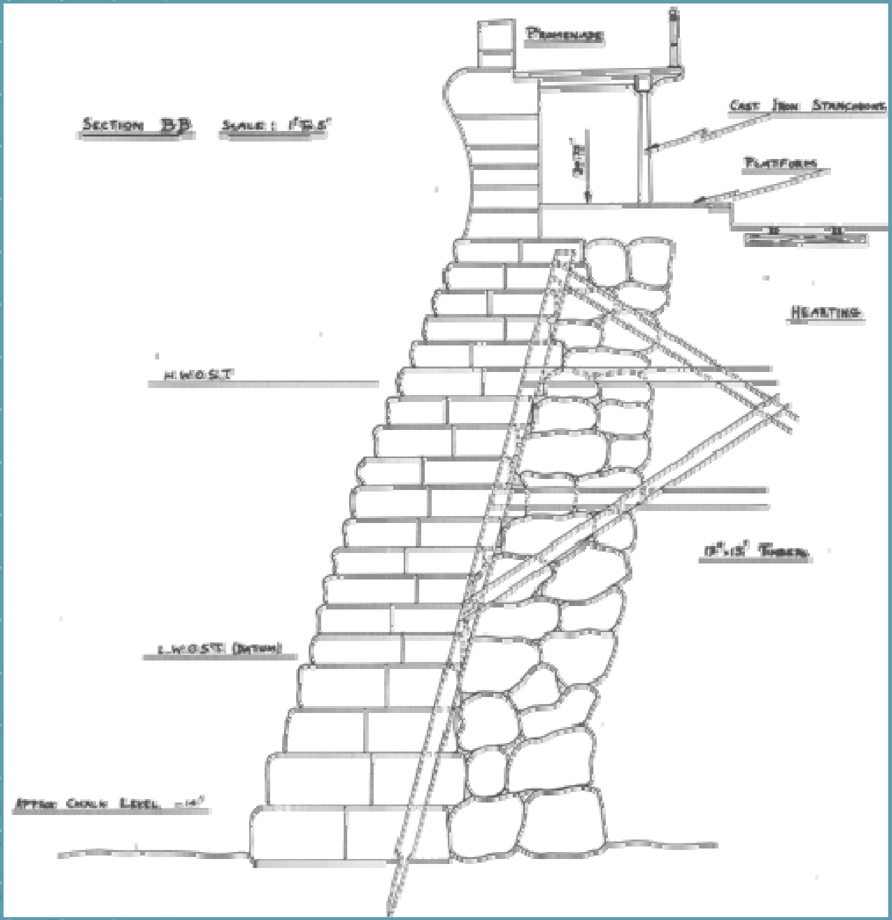
Dover harbour, 1880 - 1900

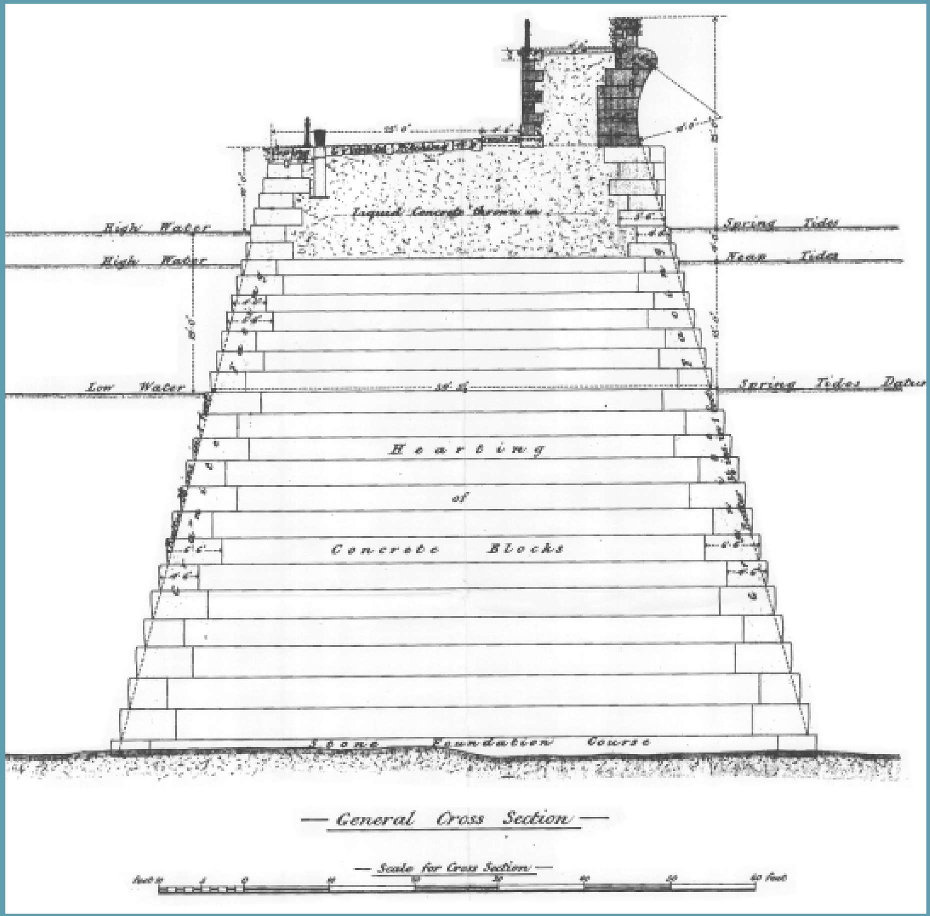
Dover harbour, 1880 - 1900



Dover breakwater, showing concrete blocks, use of bag joggle jointing, no foundation mound. Required large plant and divers

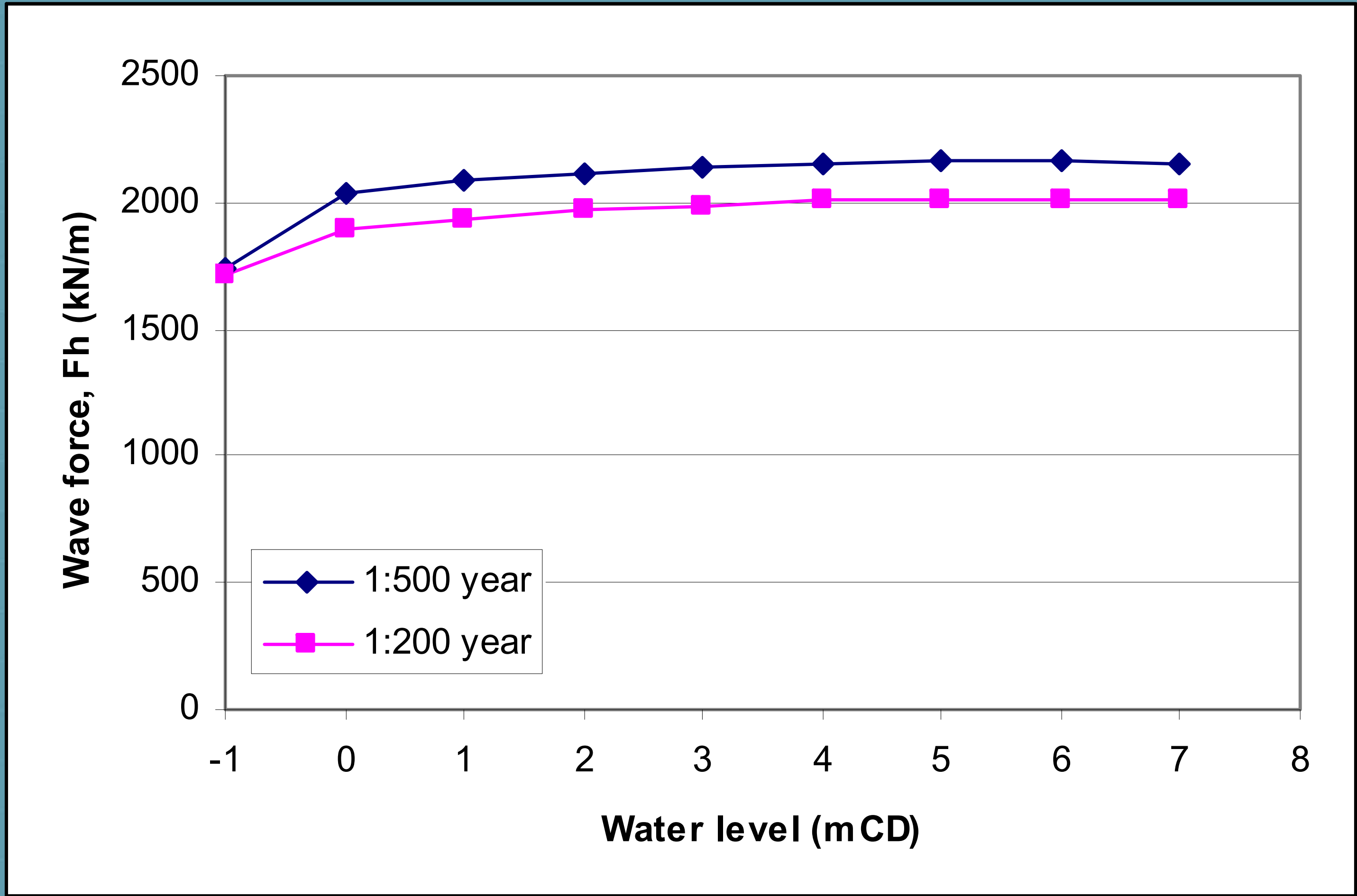
Dover harbour, 1880 - 1900





Dover harbour, 1880 - 1900

Dover – wave loads



Non-impulsive loads calculated by Goda's (1985, 2000) method.

Admiralty Breakwater, Alderney

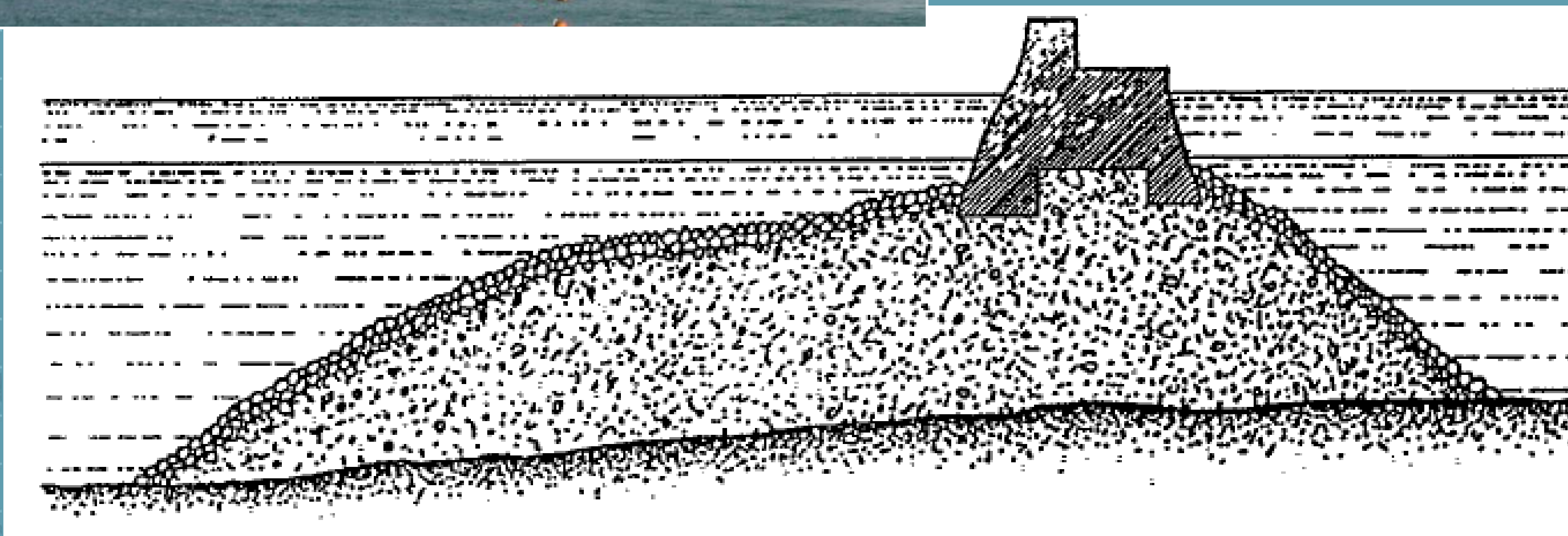
1847-present

Admiralty breakwater, Alderney

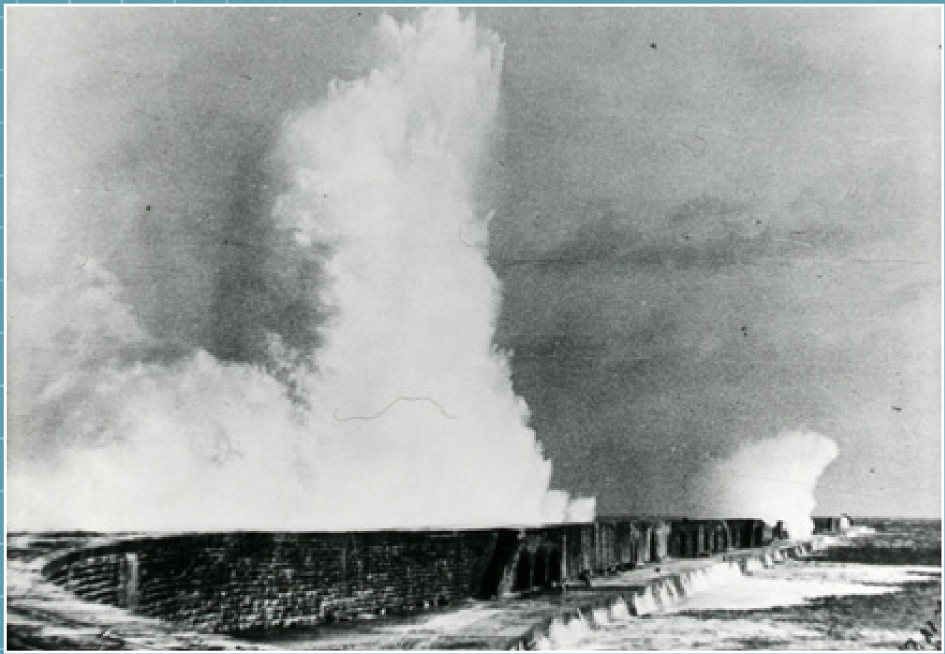
Admiralty breakwater, Alderney

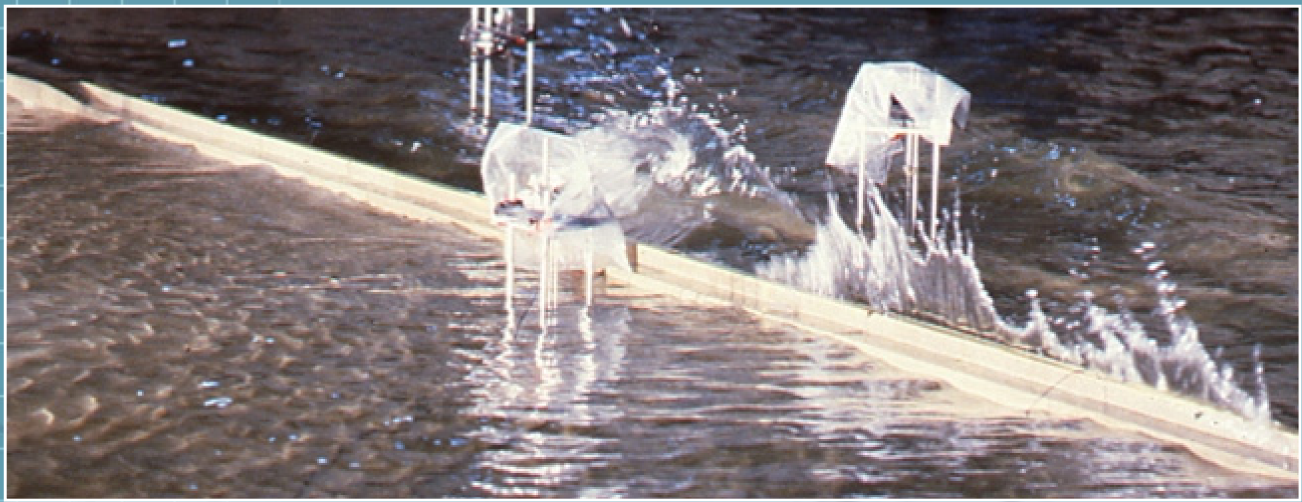
Admiralty breakwater, Alderney

High mound causes (longer) waves to shoal up and break impulsively against the upper wave wall



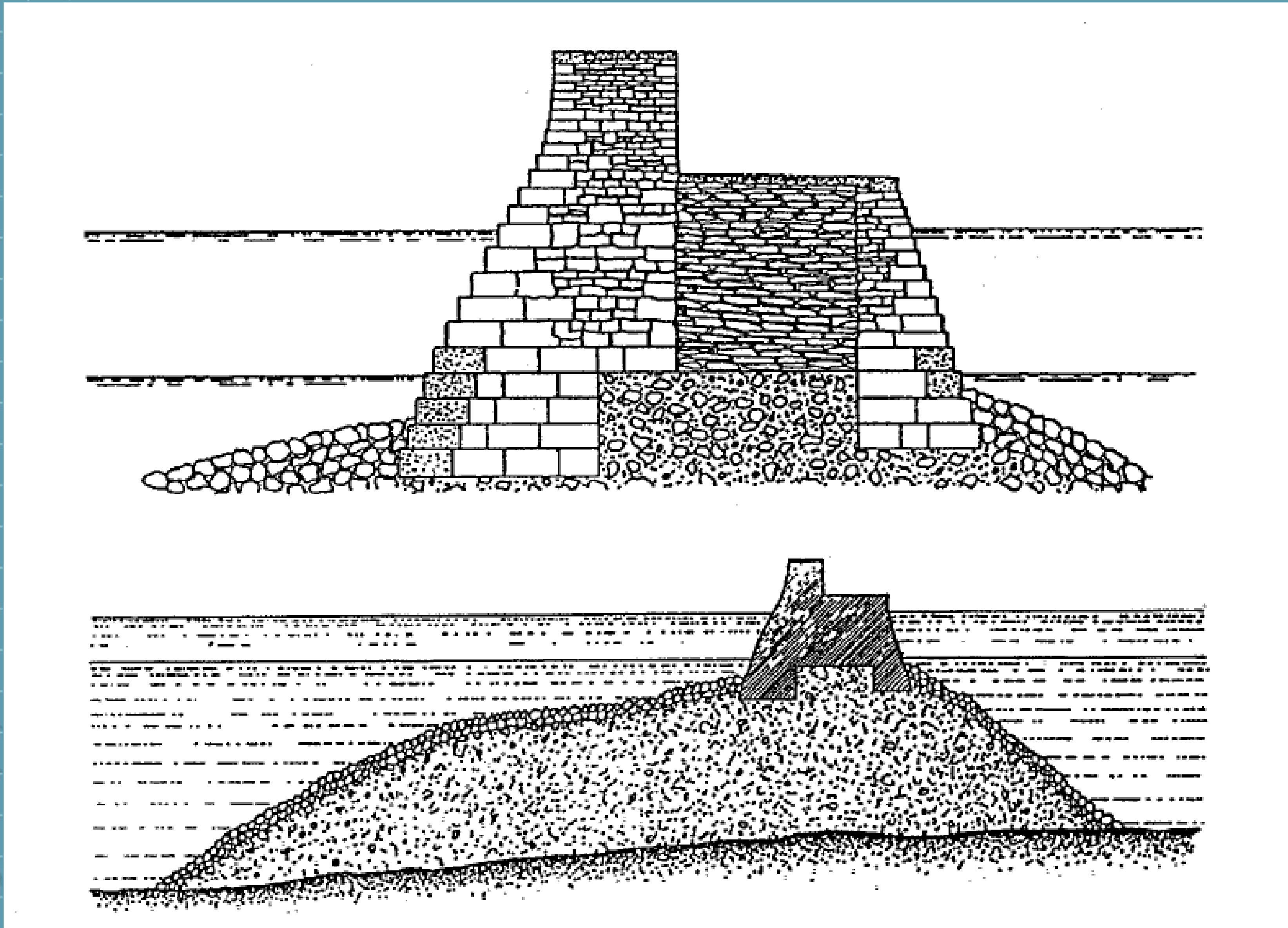
Alderney Breakwater under storms





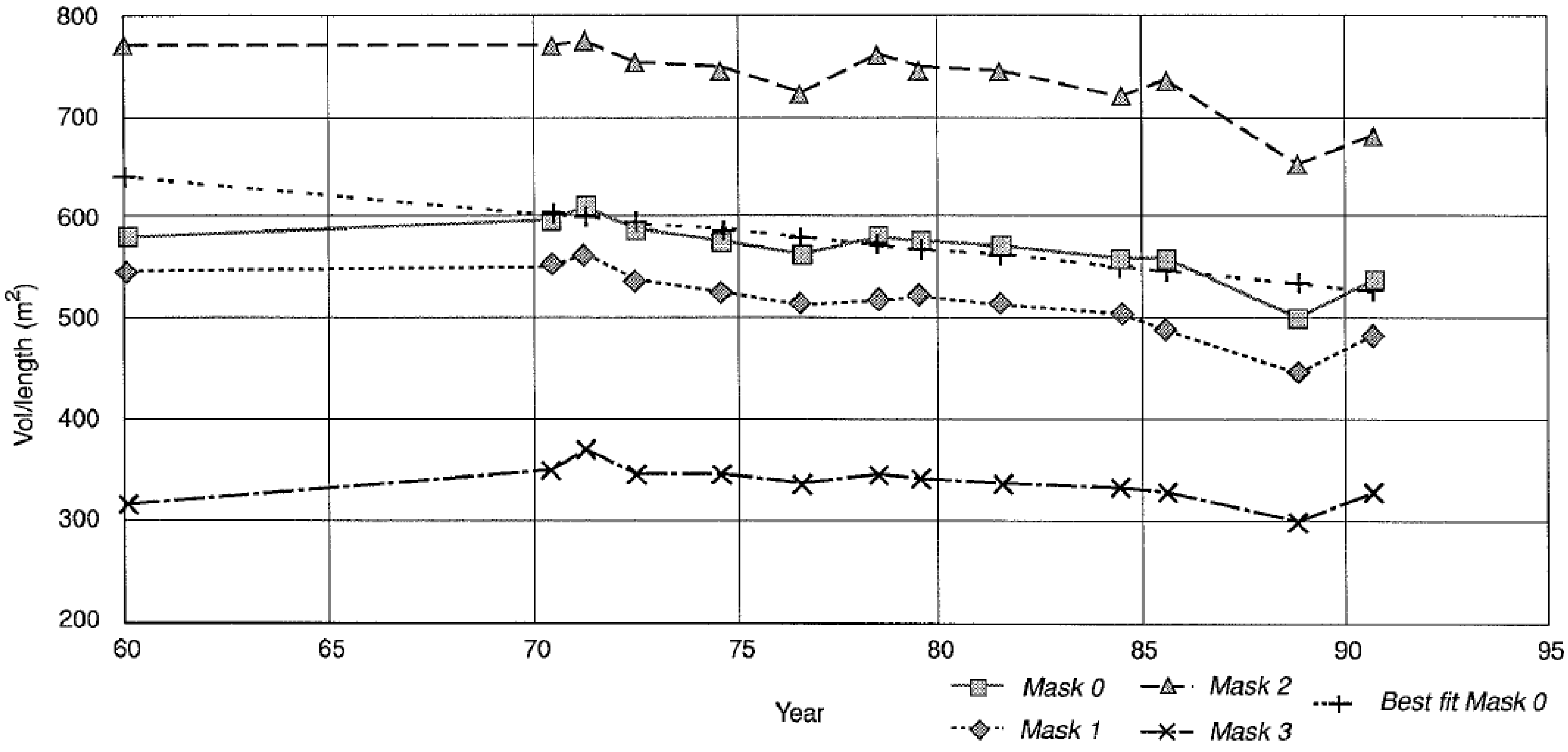
Alderney Breakwater – damage repair

Admiralty breakwater, Alderney



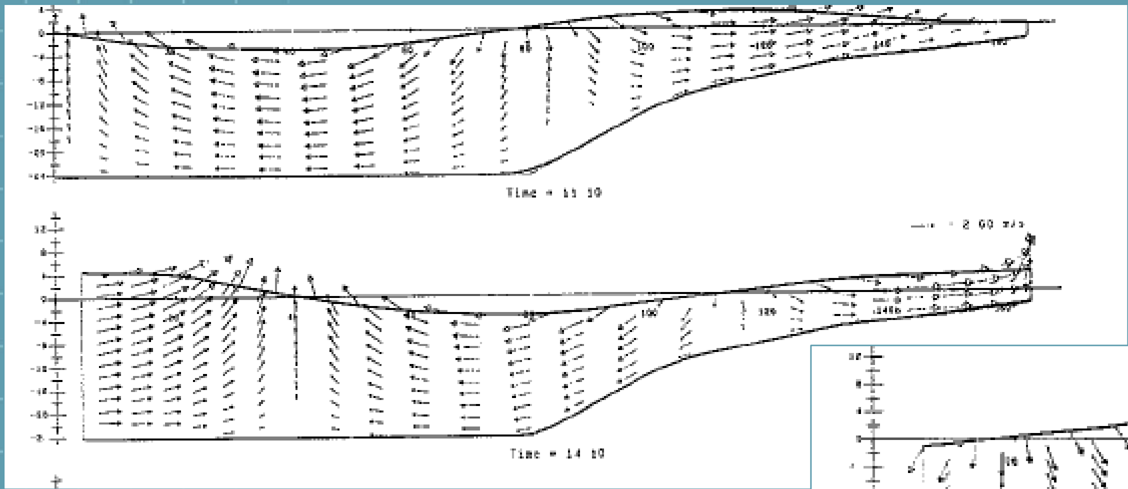
Alderney – loss of mound material

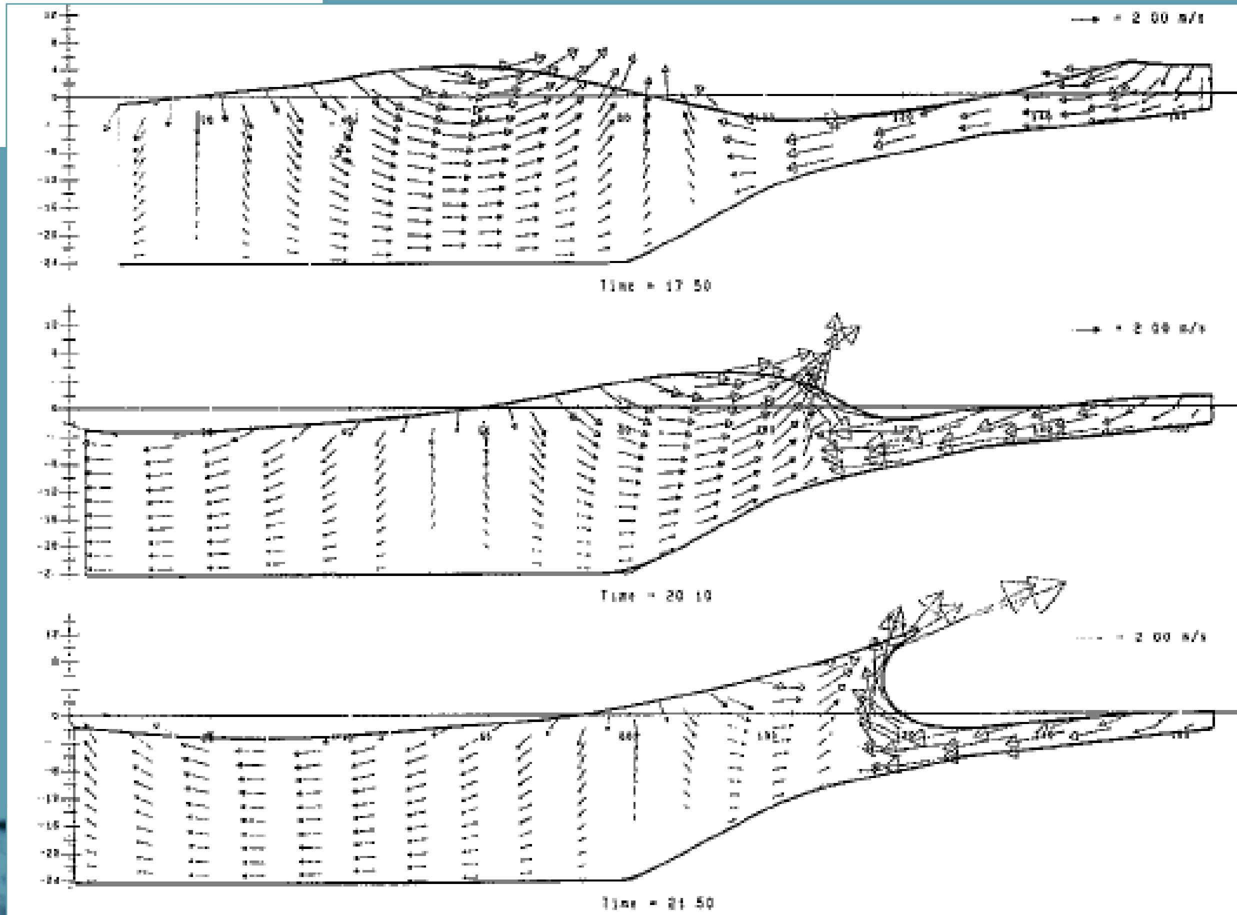
Mound losing 3000 – 6000m^3 per year,
rate of loss tending to accelerate 1990 - 1993



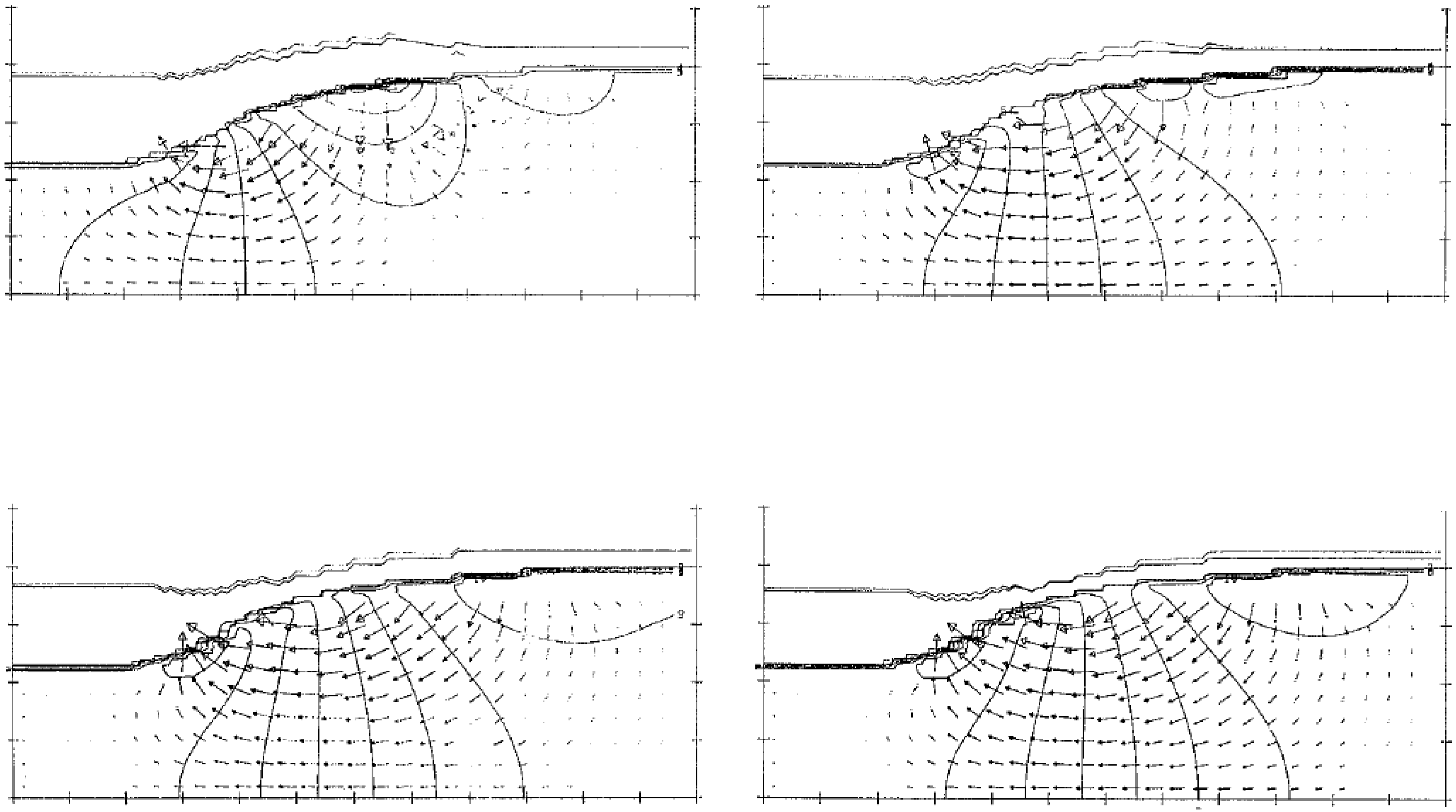
Changes to the mound volume, 1960-1990

Alderney – wave velocities / pressures

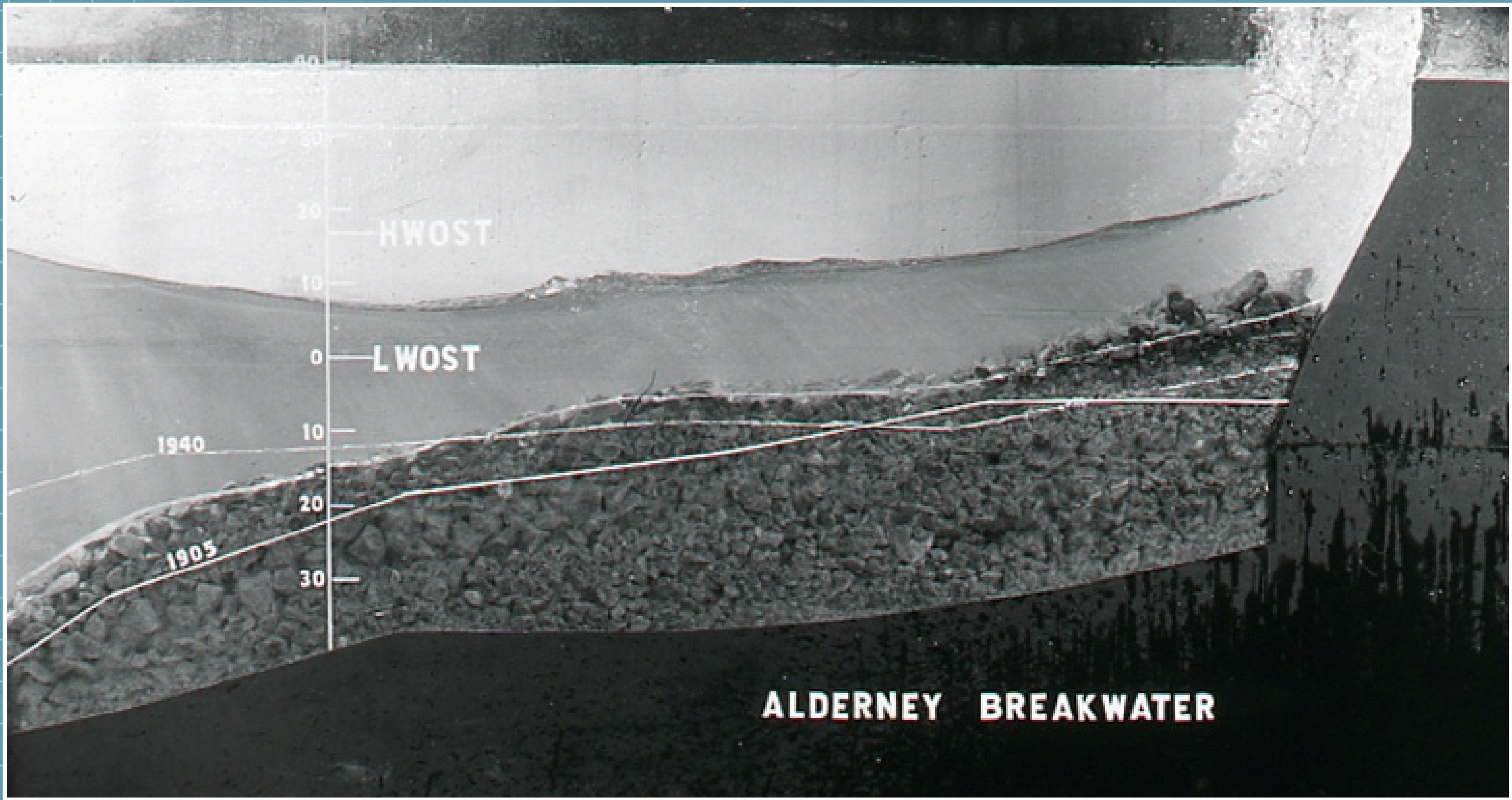




Alderney – pressures within the mound

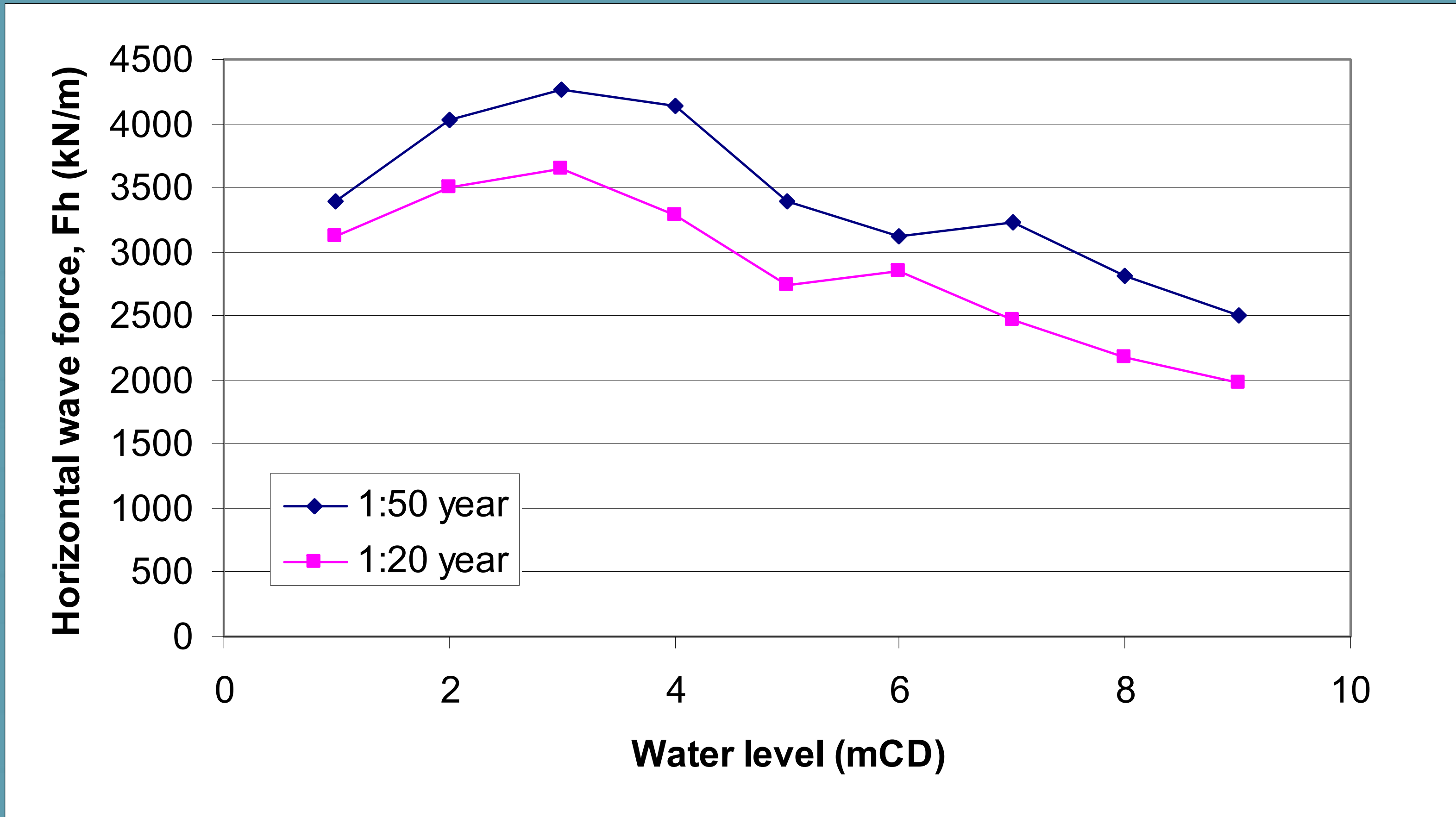


Alderney – wave loads



HRS model tests (circa 1965) studying movement of the mound material.

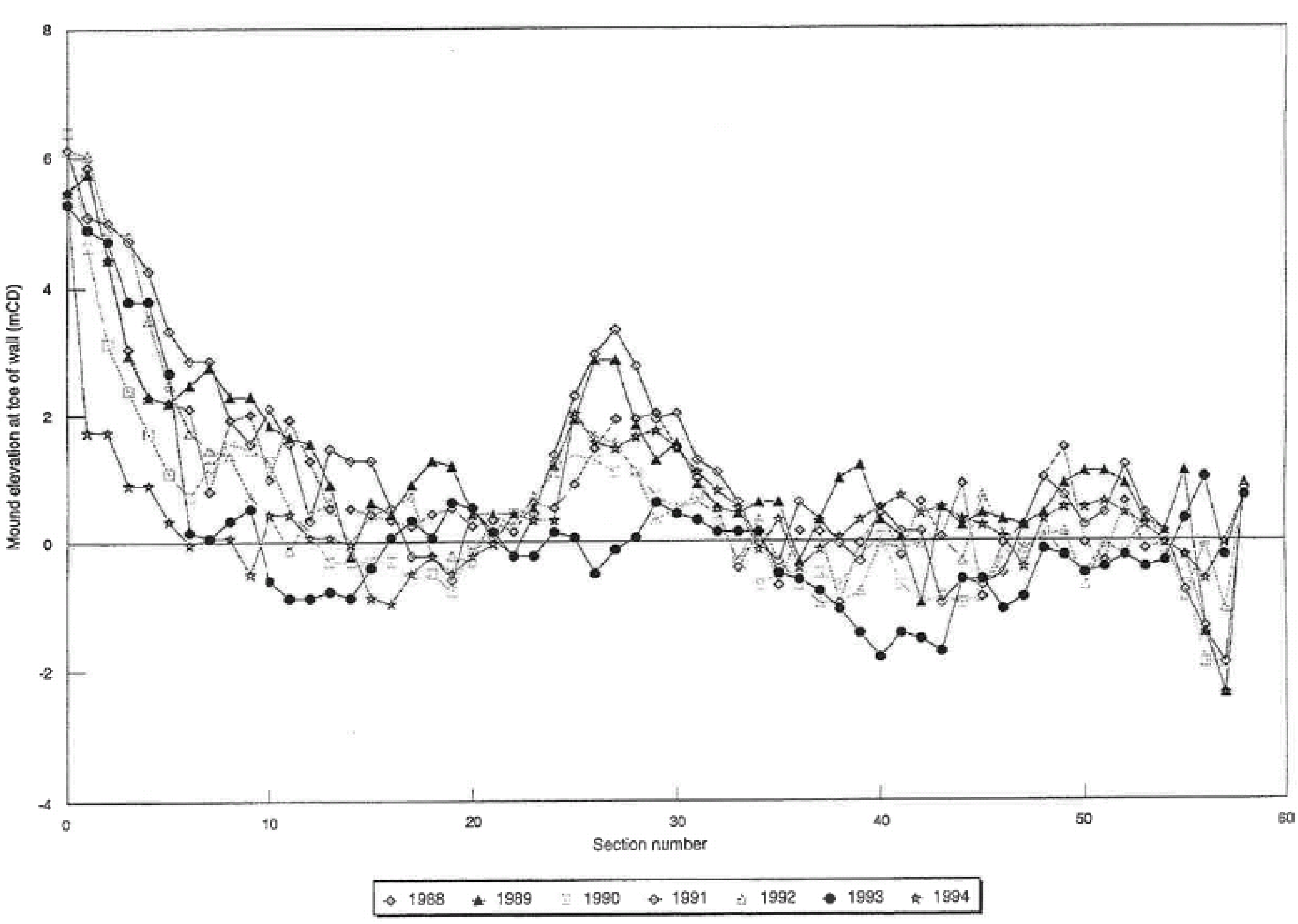
Alderney – wave loads



Wave loads (per m run) calculated using Goda + Takahashi for 1:50 or 1:20 year waves of H_s = 8.4m (or 7.4m).

NB This does not calculate spatially limited impact pressures which could be 5-20 times greater.

Alderney – the “dip” measurements



More recently, Hitachinake

Pre-cast concrete caissons for Hitachinake port constructed on land, slid into launching dock, and floated out to position.

HR Wallingford
Working with water

Even more recently, Costa Azul

Pre-cast concrete caisson breakwater for Costa Azul in Mexico, constructed in (temporary) dry dock, towed out to position.

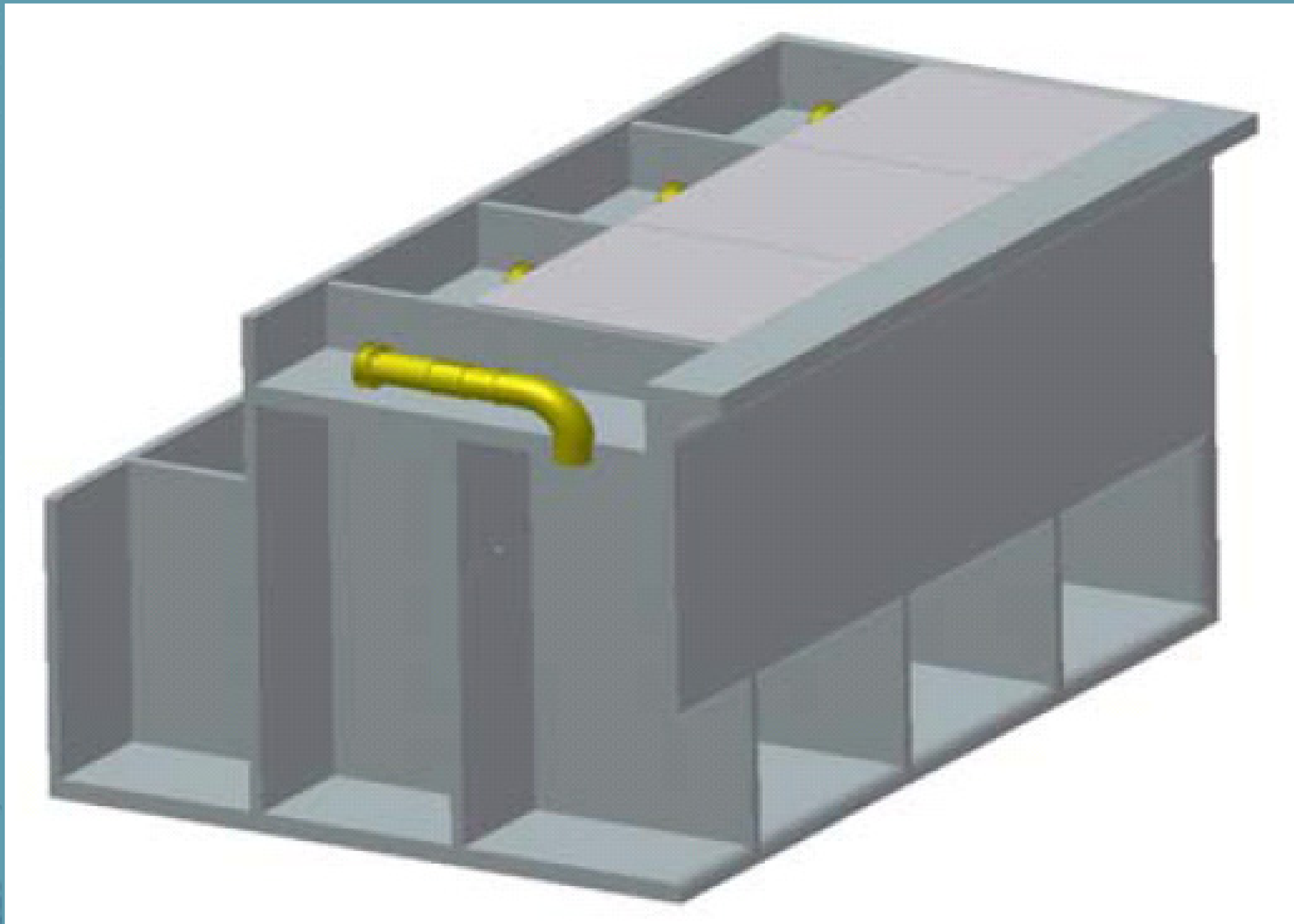
and finally, Mutriku, Basque country

Mutriku, Basque country

Expansion of Mutriku harbour, new outer breakwater with 16 Oscillating Water Column chambers in vertical wall section

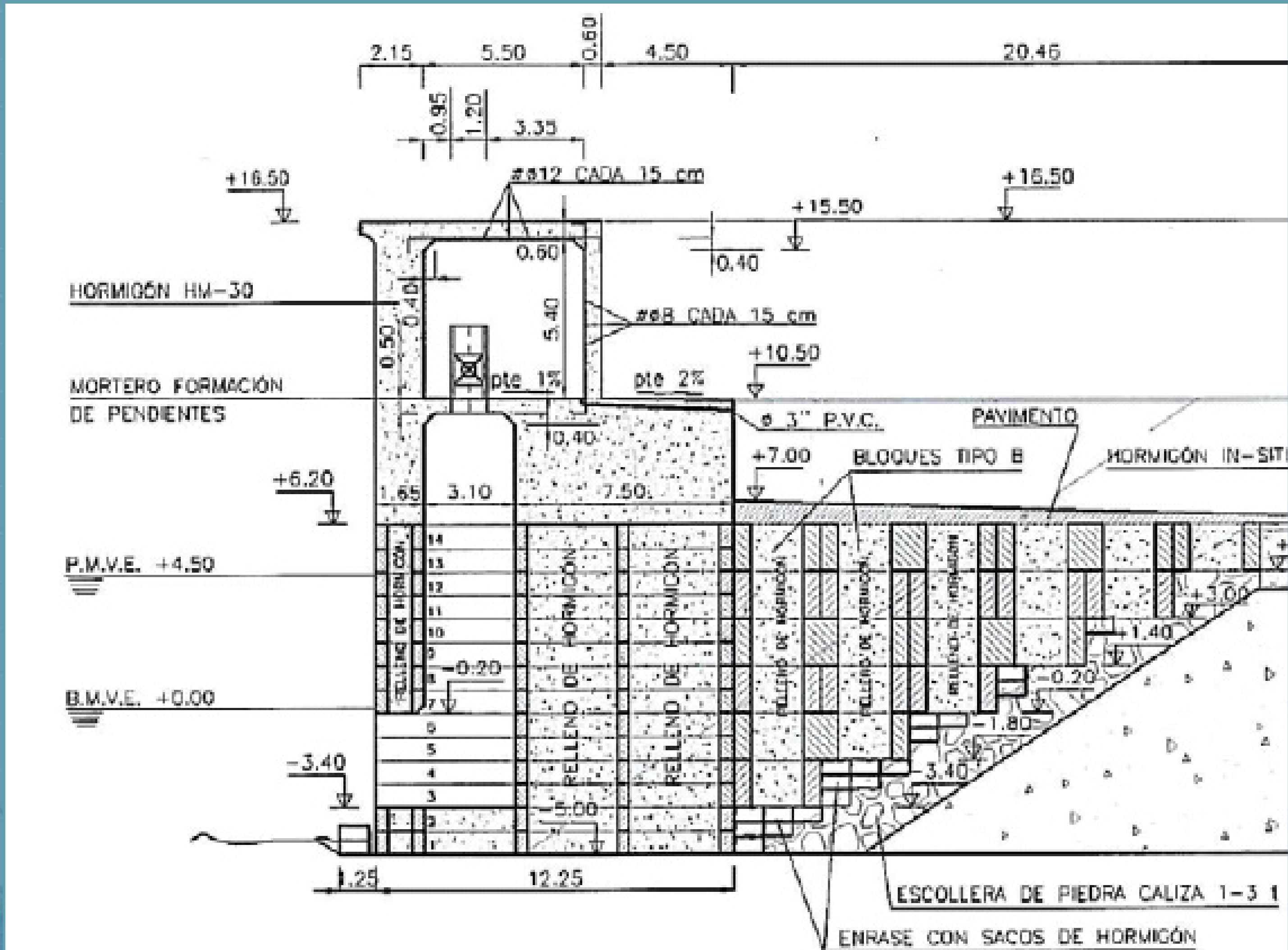
Mutriku, Basque country

Early proposal for Oscillating Water Column chambers formed in precast caissons



Mutriku, Basque country

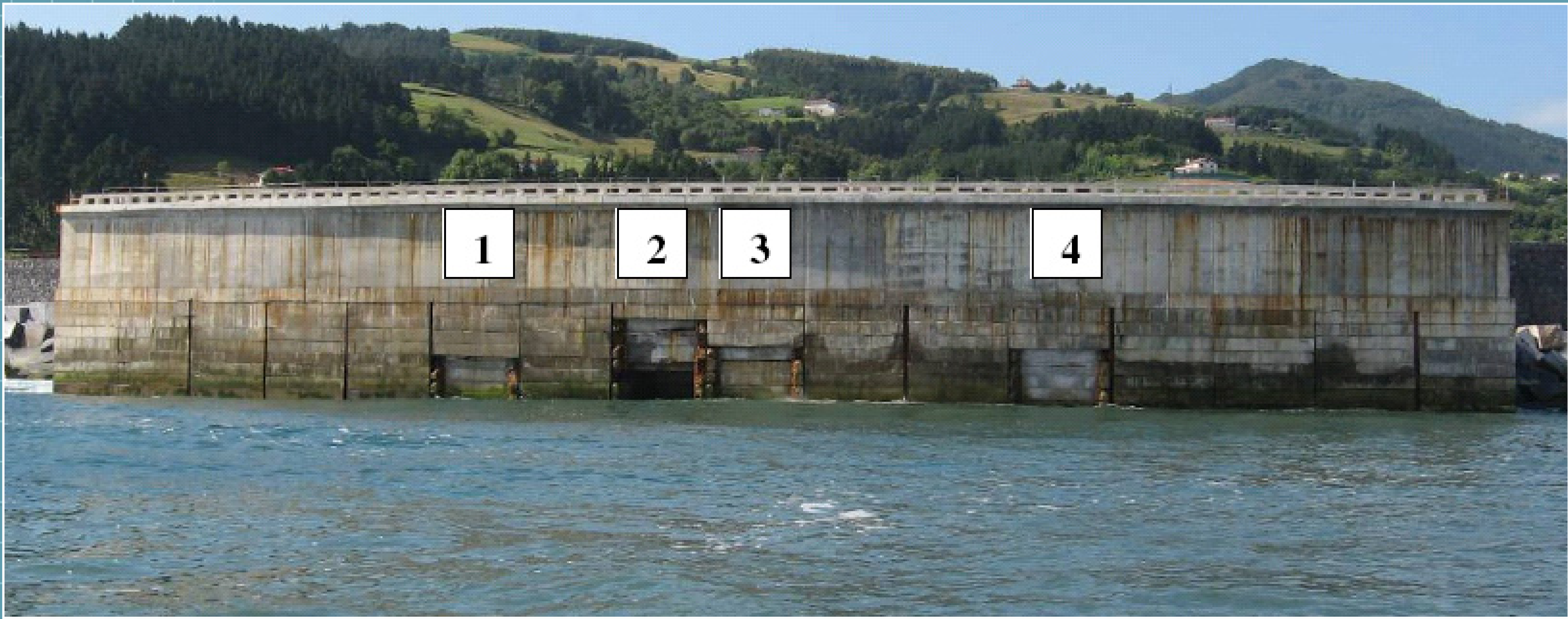
Contract awarded for Oscillating Water Column chambers constructed using precast “ring” sections to form vertical wall



Mutriku, Basque country

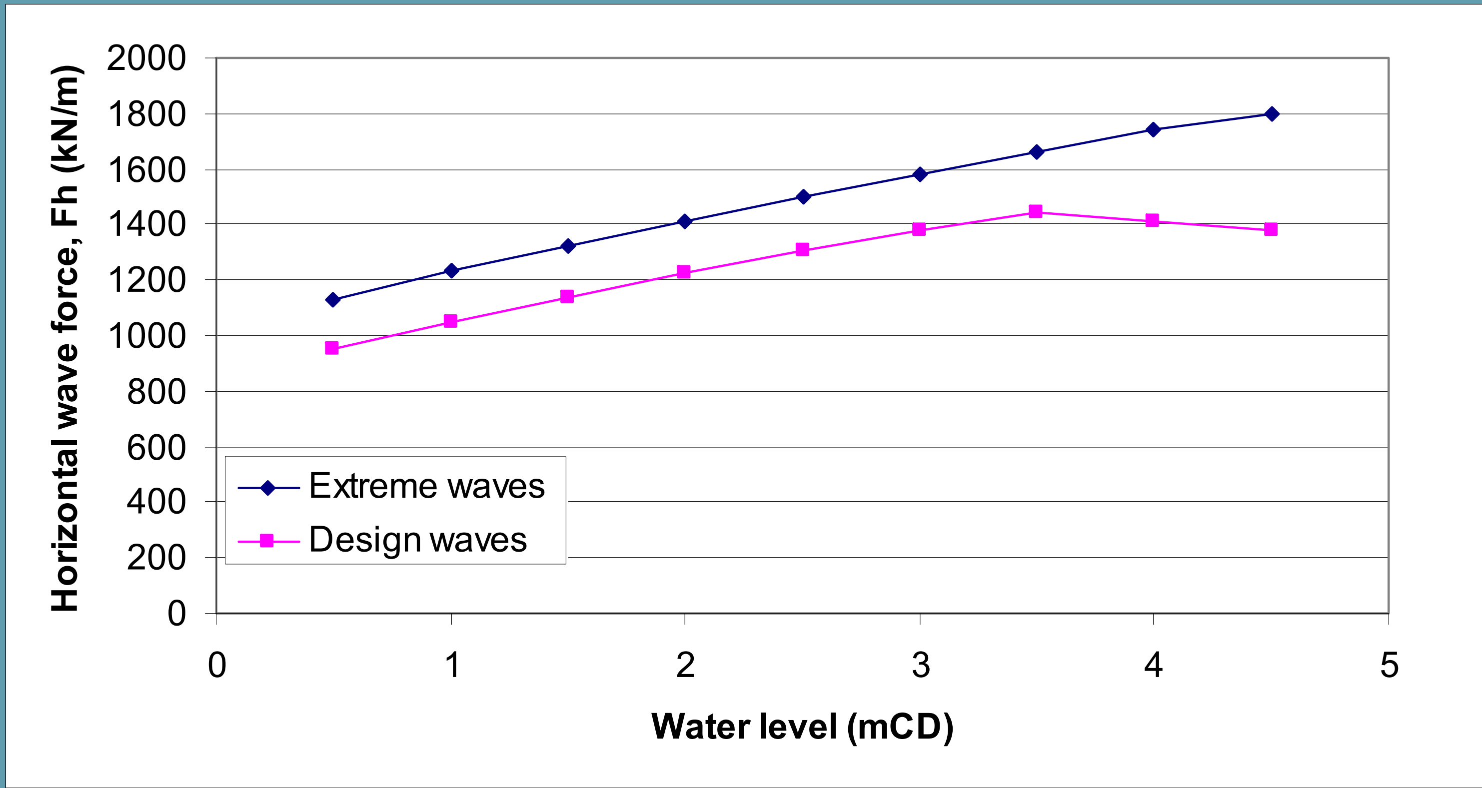
Construction of OWC breakwater using precast "ring" sections to form wall and chambers

Mutriku, Basque country



Mutriku, Basque country

Mutriku – wave loads



Wave loads (per m run) calculated using Goda + Takahashi for 1:10 bed slope, design wave of H_s = 5m, and extreme (revised?) condition of H_s = 8m.

Conclusions, and further remarks

- Essential to understand the wave loading regime
- Understand the composition of the structure when built, and now, and in the future
- Dynamic analysis essential for all structure experiencing impulsive loads
- Appropriate permeability gradients, avoid reverse or steep hydraulic gradients
- Alderney breakwater – see 1991 paper.
- Where next?

Design / analysis of vertical breakwaters

a) Design / construction of vertical breakwaters was primarily based on experience for much of the 1800s (and 1900s)

b) Changing technology altered construction methods, in turn changing key design decisions;

c) Momentum based (non-impulsive) wave loads are well predicted by the semi-empirical methods of Goda (1985, 2000)

d) Impulsive loads can exceed non-impulsive loads by 5-50 times, but are limited spatially and in duration

Design / analysis of vertical breakwaters

e) Analysis of impulsive load effects must use dynamic methods

f) Performance of blockwork systems depends critically on the permeabilities of outer and inner "layers"

g) Stability of individual blocks depends on impulsive pressures, internal transmission of short duration pressures, and structural support from adjoining blocks and the foundation

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This presentation (and papers completed / to follow) would not have been possible without essential input and/or support from:

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