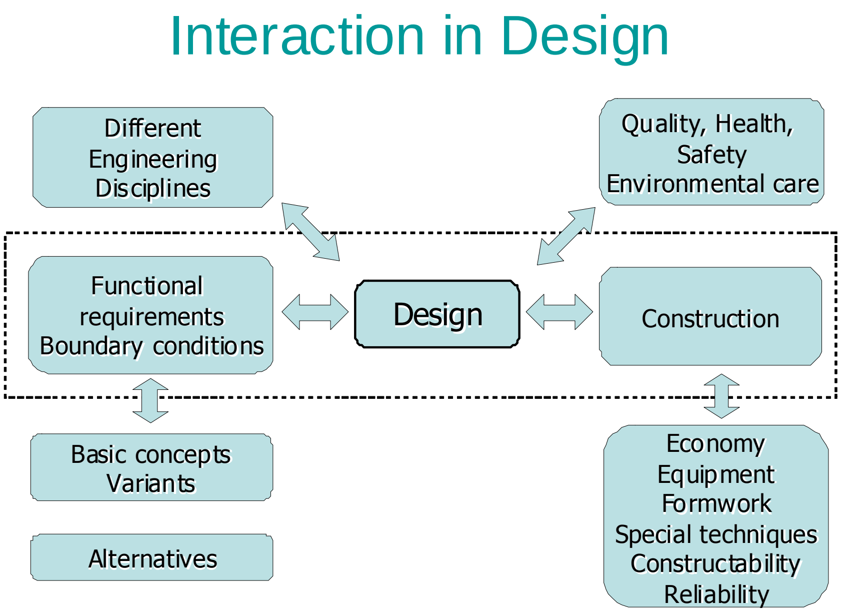
DESIGN OF QUAY WALLS

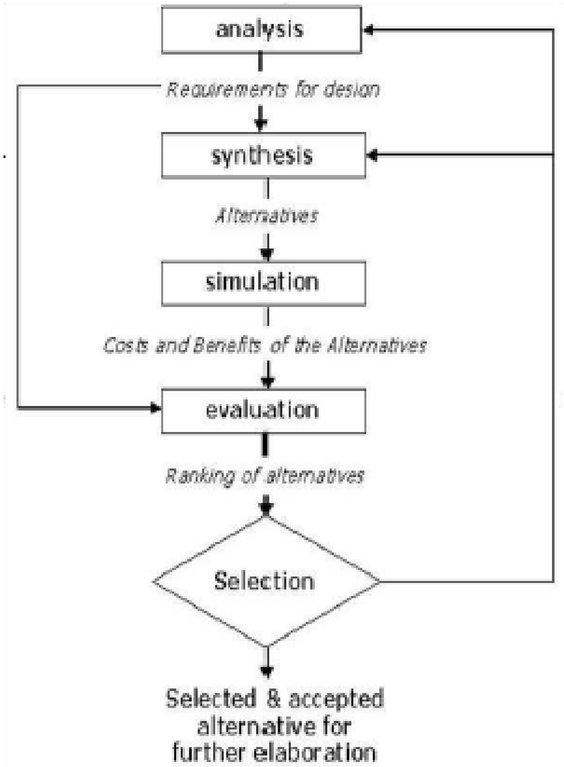
Design Rules – Design methodology (in general)

Main features of design approach considers mutual relationships of various subjects in the design process.



Ultimate objective of design process is to produce the optimum design that satisfies func. requirements as result of balancing various sometimes conflicting aspects like: construction cost, durability, robustness

General scheme for structured design approach:



In the analysis phase, the project is analyzed on:

- **Functions (Functie analyse)**
- **Operational aspects (Proces analyse)**
- **Requirements and boundary conditions**
- **Starting-points** or Assumptions

The analysis phase results in a:
List of Requirements or Specifications
or Basis of Design
or Terms of Reference (ToR) in tender documents

Functional design aspects for a Quay wall

Most important functional requirements that a quay must satisfy, are defined in consultation with the client, terminal operator and manager of the quay facilities.
These requirements are set down in terms of reference TOR.

In a design process progressed in phases like

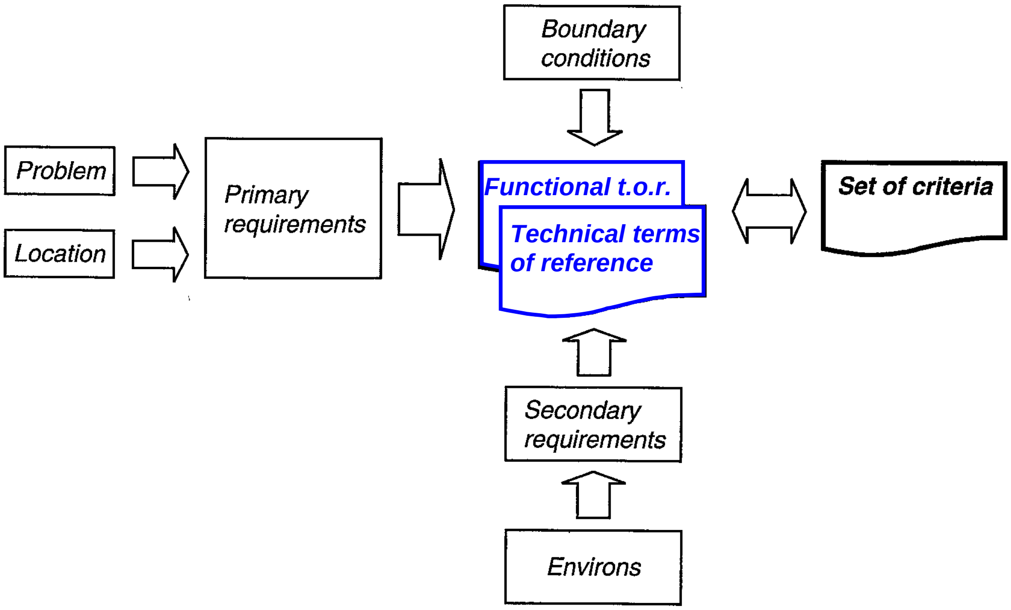
- **Feasibility studies**
- **Preliminary design**
- **Final design**

the terms of ref. are defined with increasing accuracy

Development of schematic functional design is necessary to have an idea of the effects of the various funct. req's on the design

To avoid impossible or conflicting situations one should coordinate and harmonize the req's with different authorities in relation to:

- **Arrangement and layout of the superstructure**
- **Basis of design for the front quay**
- **Determination of water depth**
- **Possible combination of loads**
- **Clearness of internal interactions of forces due to external loads**



Functional Terms of Reference (FTOR)

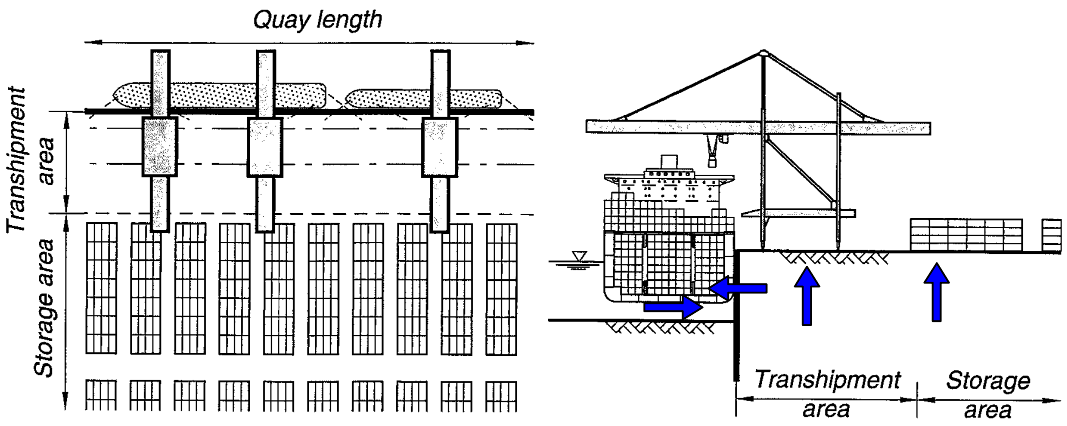
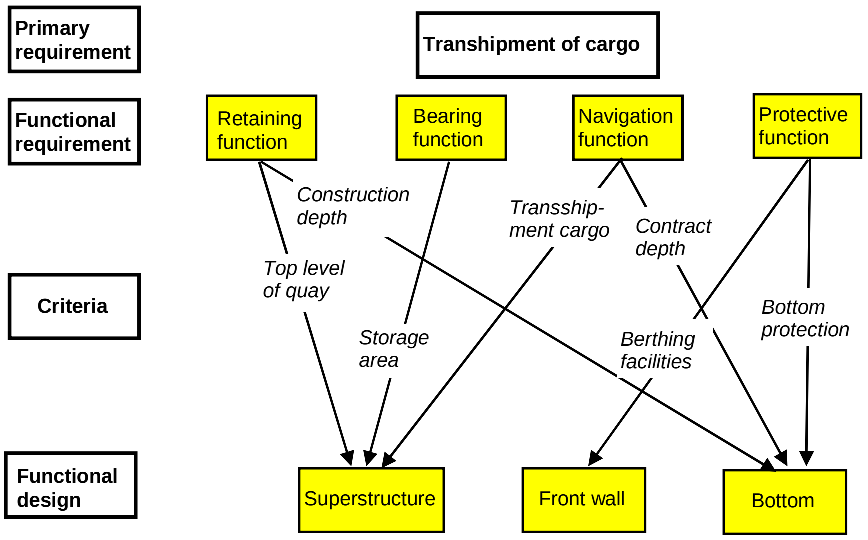


Fig. 5.2 Functional design of the quay.

- **Retaining function**: *quay wall must be able to safely retain both soil and water*
- **Bearing function**: *able to bear loads of cranes, vehicles and stored goods freight cargo*
- **Protective function**: *ships must be able to berth the quay*
- **Navigation function:** *transshipping of the cargo*

Criteria to make the functional requirements measurable are:

- *Construction depth*
- *Top level quay*
- *Storage area*
- *Transshipment of cargo*
- *Contract depth*
- *Berthing fac.s*
- *Bottom protection*



Summary Functional Terms of Reference

1. **Introduction**
   - *This gives a brief description of the project.*

2. **Boundary conditions**
   - *Description of the existing situation*
   - *Environmental conditions such as water levels and wind*
   - *Existing operational situation*

3. **Requirement**s

3.1 Navigation requirements
- *Types of ship characteristic parameters including length, beam and draught*
- *Number and length of berths*

3.2 Bearing requirements
- *Width of transshipment area*
- *Number and types of cranes + characteristic parameters*
- *Dimensions of the stack area*
- *Sort and volume of freight to be handled and stacking method*

3.3 Retaining requirements
- *Top level of quay*
- *Seabed level*

3.4 Protective requirements
- *Berthing/mooring facilities (fenders, bollards)*
- *Bottom protection*

Technical terms of reference (TTOR)

T.T.O.R. describes the technical aspects that the structure must satisfy in detail resulting in a transition of functional content to technical content.

The owner gives the FR and the designer works out to create a TTOR
After approval by the owner and terminal operator the TTOR forms the basis of design.
The project is now less abstract and the TReq can be set down in detail. The degree of detail depends on the phase the design (project) has reached Preliminary design or Final design

First agreement should be reached about the FReg and later about TReq

- **Boundary conditions** such as:

  Environmental conditions,
  - Topographical conditions (*arrangement of natural and artificial physical features of the port area*)
  - Hydrographic, Hydraulic conditions *(water levels, torrent, waves)*
  - Geotechnical conditions *(soil properties)*
  - Meteorological conditions *(annual precipitation/rainfall, snow)*
  - Disturbance in the subsoil (*weak strata, polution*)

  Presence of cables and pipelines

  Existing operational situation

REQUIREMENTS

- **Navigation, function** (*Nautical length, . Dimensions of quay wall)*

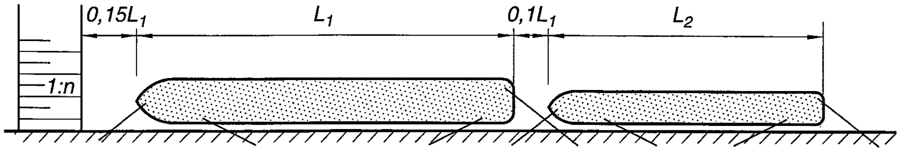
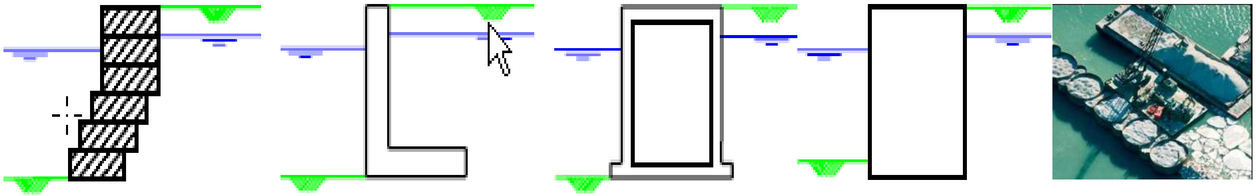


Fig. 5.4 Mooring configuration for two ships.

- **Retaining function** *(gravity quay wall type)*



- **Bearing function**

  Data of freight

  Data of cranes and vehicles

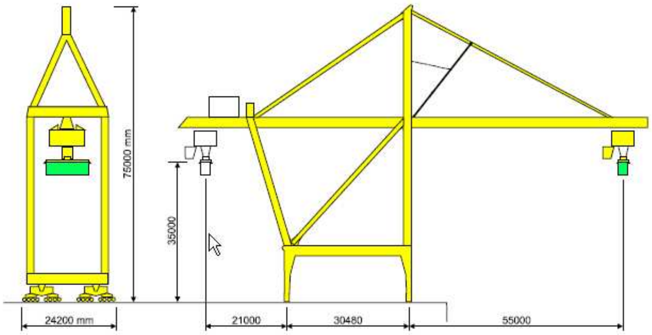


Fig. 5.12 Bogie of a portainer crane.

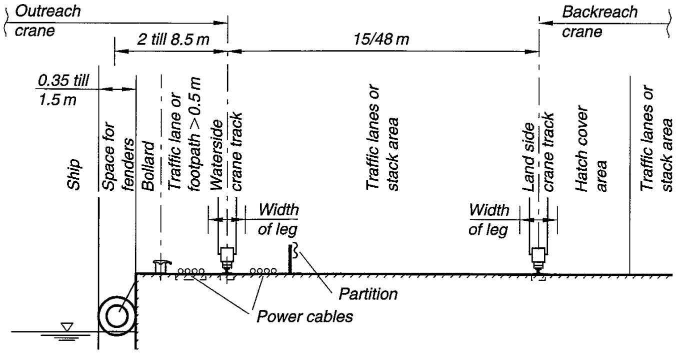
- type, rail gage

Detail: Bogie of portainer crane

- self weight, max.wheel loads, max wheel distance

- lifting capacity on waterside /on landside,

- Layout of transsphipment area



- Crane track facilities (*details of crane track, Criteria for use)*

- **Protective function**

  Mooring facilities: *fenders bollards)*

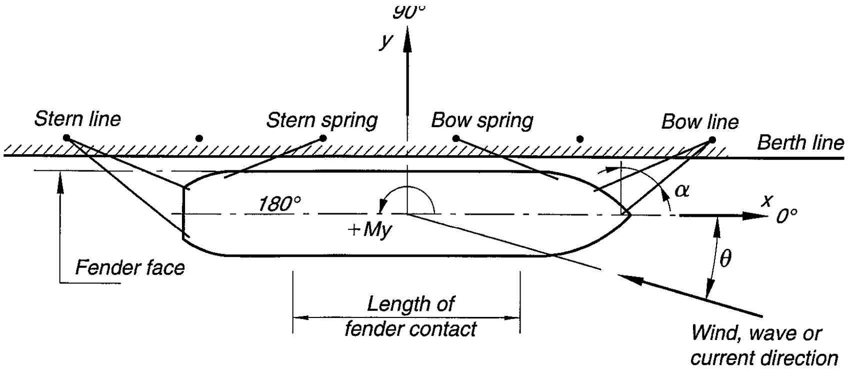


Fig. 5.5 Mooring configuration.

Harbour bed

Harbour bed protection

Shore protection

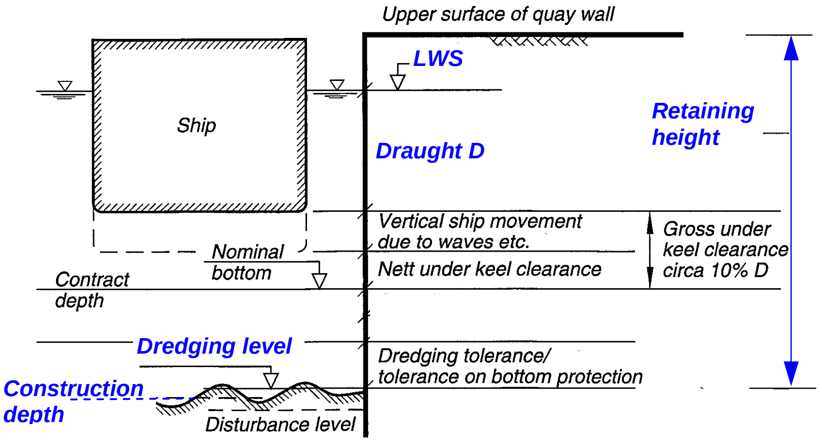


Fig. 5.7 Factors influencing contract and construction depth.

Maintenance requirements and management aspects

- **Diverse**

  Public utilities, lighting, drainage, signage

- **Safety aspects/reporting and permits**
- **References**

  Procedures, guidelines, standards, legal aspects

- **Annexes A**

  Drawings, load diagrams

Summary Technical terms of reference

1. Introduction

This gives a brief description of the requirements. The objective of the project, the organisation, planning, and possible phasing and functional requirements are described.

2. Boundary conditions

2.1. Description of existing situation

2.2. Environmental conditions, such as
- *Topographical conditions*
- *Hydrographic conditions*
- *Geotechnical conditions*
- *Hydraulic conditions*
- *Meteorological conditions*
- *Disturbance in the subsoil*

2.3. The presence of cables and pipelines

2.4. Existing operational situation

3. Navigation function .

3.1. Nautical basis
- *Usable length of berths (nautical length)*
- *Type of vessel*
- *Details of main propellers*
- *Details of bow thrusters*

3.2. Dimensions of quay wall

4. Retaining function

4.1. Structure of the quay wall

5. Bearing function

5.1. Data of freight (sort and volume, stacking method)

5.2. Data of cranes and vehicles

5.3. Crane track facilities
- *Details of crane track*
- *Criteria for use*

6. Protective function

6.1. Mooring facilities

6.2. Harbour bed

6.3. Harbour bed protection

6.4. Shore protection

6.5. Maintenance requirements and management aspects

7. Diverse

Public utilities, lighting, drainage, signage

8. Safety aspects/reporting and permits

9. References

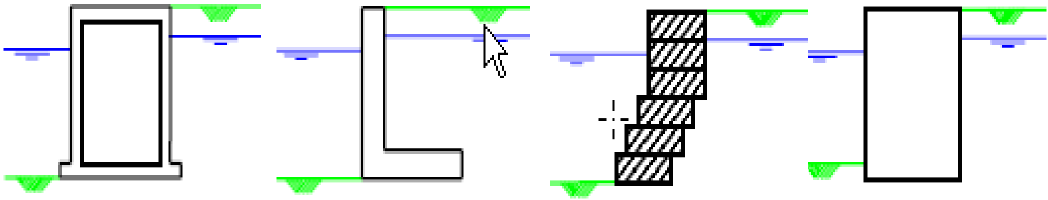
9.1. Procedures, guidelines, standards, legal aspects

10. Annexes A

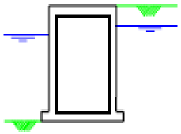
Drawings, load diagrams

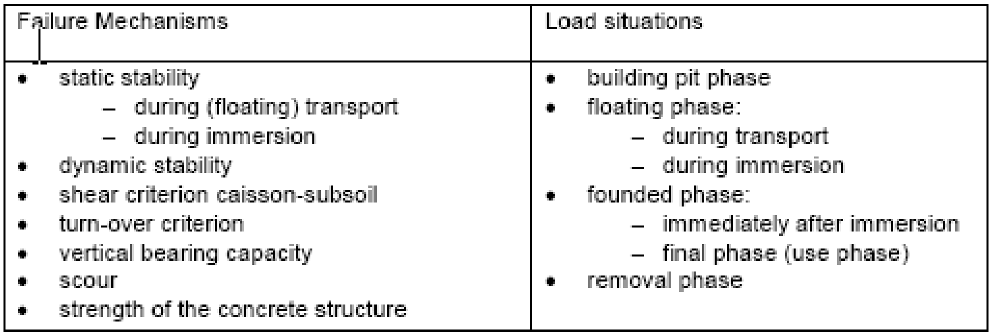
Structural design of a quay wall

Alternatives to be selected



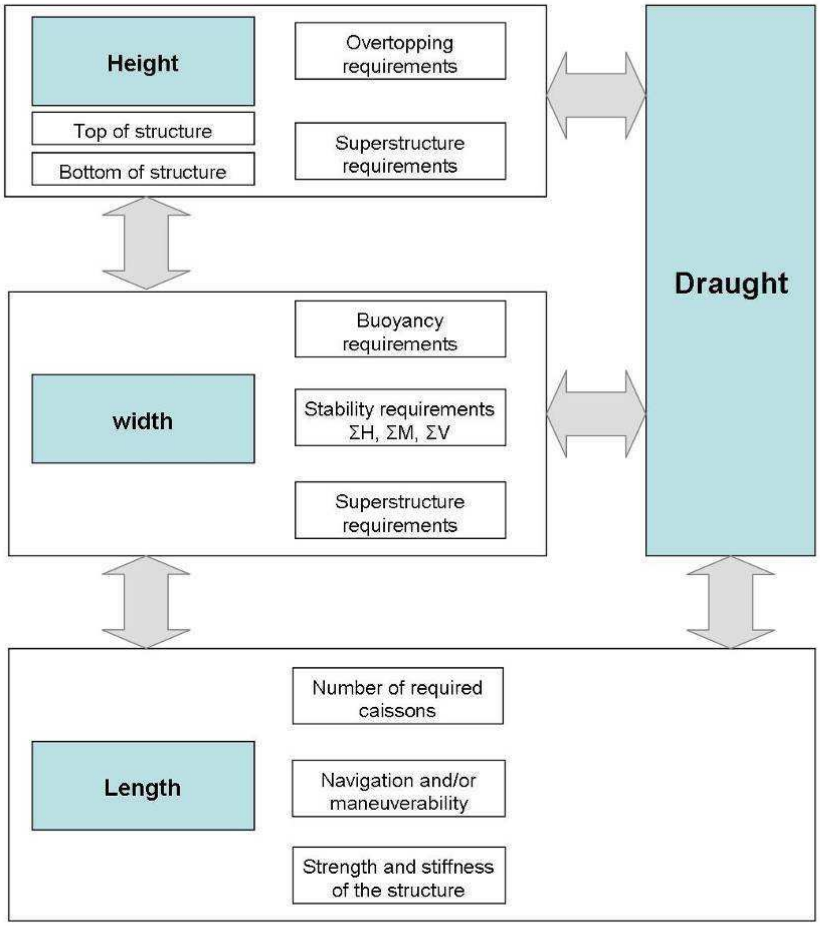
Failure mechanisms and load situations for a caisson





Failure Mechanisms	Load situations
• static stability – during (floating) transport – during immersion • dynamic stability • shear criterion caisson-subsoil • turn-over criterion • vertical bearing capacity • scour • strength of the concrete structure	• building pit phase • floating phase: – during transport – during immersion • founded phase: – immediately after immersion – final phase (use phase) • removal phase

Determination of the main dimensions



Step 1: **Height** subject to specification:

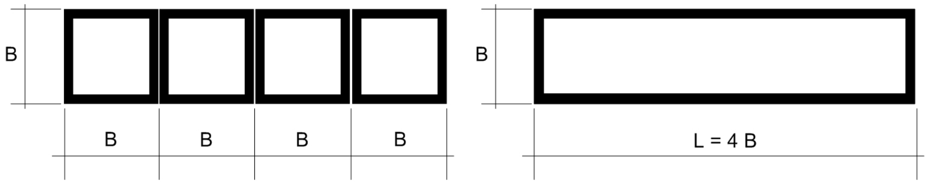
- BC's (geotechnical, hydraulic, meteorologic)
- FR's (retaining, protection

Step 2**: Width**:

Structural strength and stiffness in life cycle stages and floating condition during transport

Step 3: **Length**:

Practical construction rules (two times the caisson height/ width ratio 2:1, length/width ratio of 3:1),
manoeuvrability of the caisson,
number of joints or shear-keys
Load transfer considerations

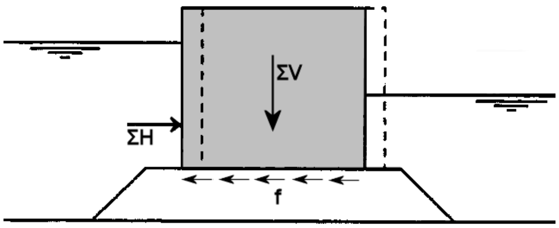


TOP VIEW

LOAD TRANSFER SIDE WALLS

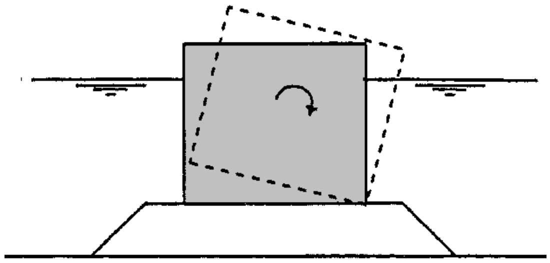
Design checks

Shear criterion caisson-subsoil: $\Sigma H < f\,\Sigma V$

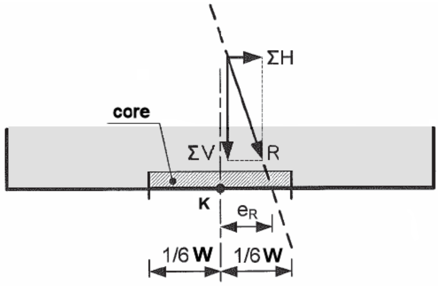


Slide-off principle sketch

Turn-over criterion



$$e_R = \frac{\Sigma M}{\Sigma V} \le \frac{1}{6} W$$



Action line of the resulting force should intersect the core of the structure

Vertical bearing capacity

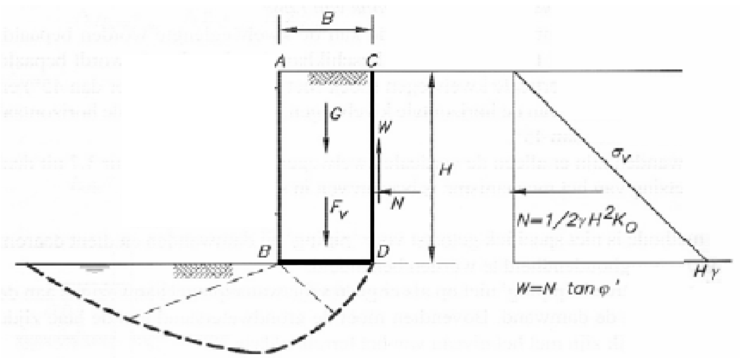
$$\sigma_{k,max} = \frac{F}{A} + \frac{M}{W} = \frac{\sum V}{W \cdot L} + \frac{\sum M}{\frac{1}{6} L W^2}$$

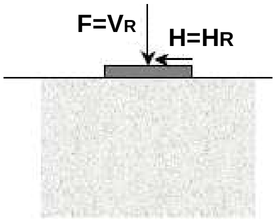
where: ΣV = total of the acting vertical forces (or vertical components) [N]
A = area of the bottom plate [m2]
W = width of the structural element [m]
L = length of the structural element [m]
ΣM = total of the moments, preferably around point K, halfway the width [kNm]

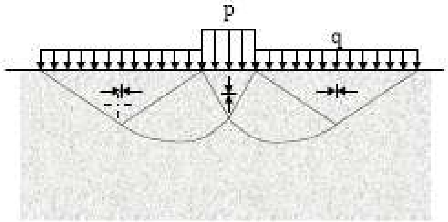
$$\boldsymbol{\sigma_{k,max} < p'_{max}}$$

Bearing capacity of the soil

Actual situation → To be calculated with Brinch Hansen







$$F_{max} = p'_{max} \cdot A$$

$$\boxed{p'_{max} = c' N_c s_c i_c + q' N_q s_q i_q + 0{,}5\gamma' B \cdot N_\gamma s_\gamma i_\gamma}$$

The bearing capacity factors are:

$$N_c = (N_q - 1)\cot\phi' \qquad N_q = \frac{1+\sin\phi'}{1-\sin\phi'} e^{\pi \tan\phi'} \qquad N_\gamma = 2(N_q - 1)\tan\phi'$$

The shape factors ($B \le L \le \infty$) are:

$$s_c = 1 + 0.2\frac{B}{L} \qquad s_q = 1 + \frac{B}{L}\sin\phi' \qquad s_\gamma = 1 - 0.3\frac{B}{L}$$

The inclination factors to deal with an eventual inclined direction of the resulting force ($B \le L \le \infty$) are:
For drained soil:

For H parallel to B:

$$i_c = \frac{i_q N_q - 1}{N_q - 1} \qquad i_q = \left(1 - \frac{0.70H}{F + Ac'\cot\phi'}\right)^3 \quad i_\gamma = \left(1 - \frac{H}{F + Ac'\cot\phi'}\right)^3$$

The reduction of the vertical bearing force *F* as a result of the horizontal load *H can be* considerable !

Design checks (concrete strength)

Ultimate limit state (ULS)

First Bending moments then Shear forces

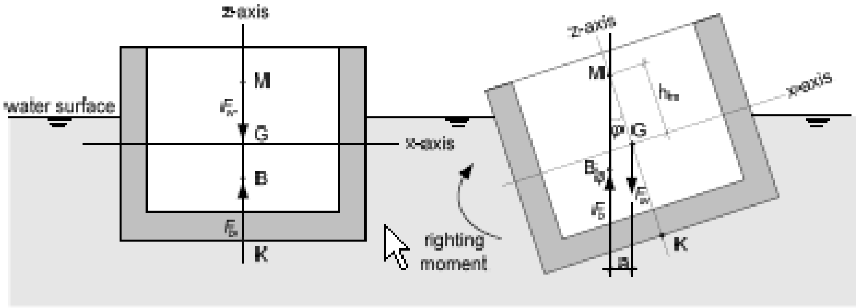
Mind different phases:

Phase I: **Caisson in building dock** (construction phase)
Not governing

Phase II: **Floating caisson during transport** (construction phase)
Governing for concrete analysis

At first check dimensions with respect to buoyance (draft) and static stability

Static stability means that a rotation, caused by external factors, is corrected by a righting moment that will return the element to its original position



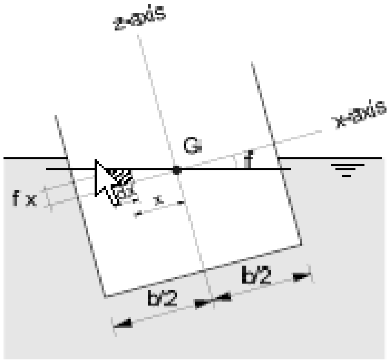
- B is the centre of buoyancy, here B is also the centre of gravity of the displaced water.
- G is the centre of gravity of the element (also rotation point.)
- M is the meta centre; the point of intersection the z-axis and the action line of the buoyant force in tilted position.

For static stability GM, (metacentric height h_m) must be positive.

$$\overline{BM} = \frac{a}{\varphi} = \frac{I}{V}$$

$$a = \frac{M}{F_b} = \frac{\varphi \rho g I}{\rho g V} = \frac{\varphi I}{V}$$

I (actually I_{yy}) is the area moment of inertia, relative to the y-axis, of the plane intersected by the waterline



Phase III: **Floating caisson** (construction phase)

Dynamic stability is **not** be checked

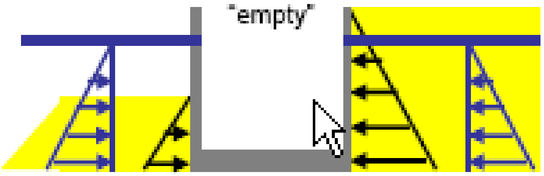
Phase IV: **Caisson** (operational phase**)**

Caisson is fully filled with sand, embedded with water pressure at the front side and soil pressure at the back side

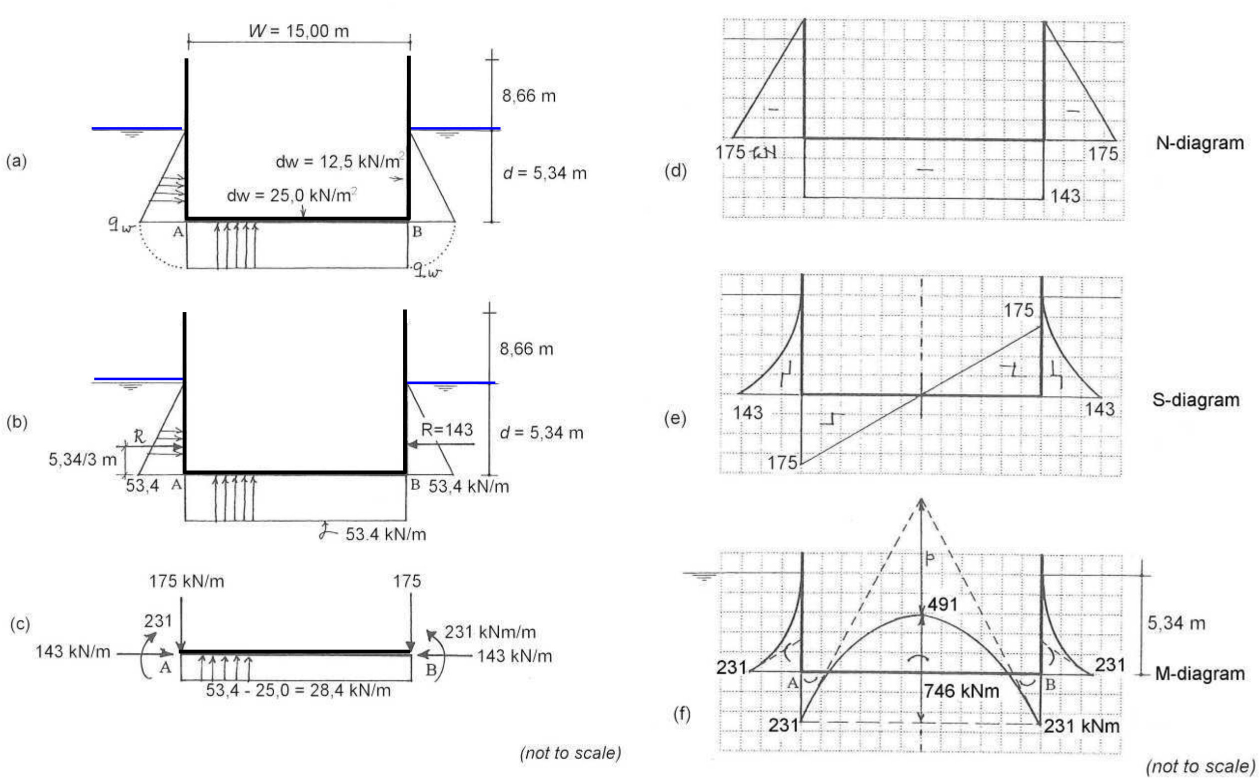
Not governing for structural analysis

Phase IIa: Floating caisson - strength check

The floating phase often is governing for the stresses in the concrete side-walls. This is caused by the combination of high water pressure outside, while there is no pressure working from inside in the empty caisson.



Symplified calculation of internal forces in wall sections (1- dimensional approach)



With help of the maximum moment and Table 8.IV (next page) the required wall thickness can be estimated. To do so, an economic reinforcement percentage has to be chosen. Assume a value of 1% For this percentage, Table 7 gives a value for

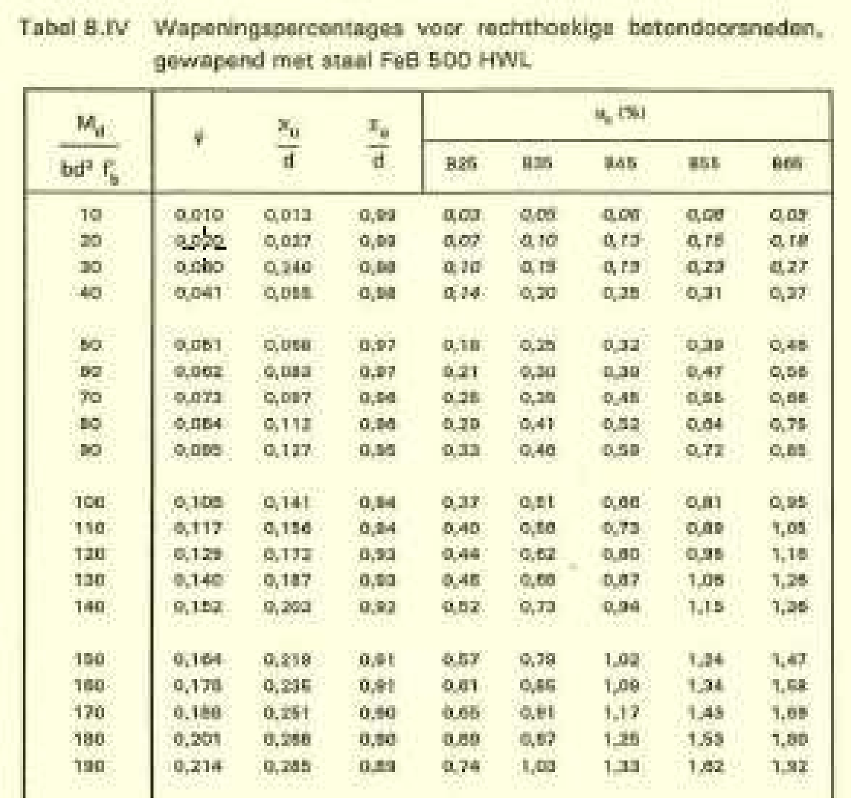
,

$$\frac{M_d \perp}{b \cdot t^2 \cdot f'_b}\,' = 150$$

So thickness is :

$$t_b = \sqrt{\frac{M_d}{b \cdot 150 \cdot f_b'}} = \sqrt{\frac{491}{1.0 \cdot 150 \cdot 27}} = 0.35 \text{ m} < 1.00 \text{ m}$$

Determination of reinforcement in concrete walls with tables



Tabel 8.IV Wapeningspercentages voor rechthoekige betondoorsneden, gewapend met staal FeB 500 HWL

$\frac{M_d}{bd^2 f'_b}$	ψ	$\frac{x_u}{d}$	$\frac{z_u}{d}$	ω_0 (%)				
				B25	B35	B45	B55	B65
10	0,010	0,013	0,99	0,03	0,05	0,06	0,08	0,09
20	0,020	0,027	0,99	0,07	0,10	0,13	0,15	0,18
30	0,030	0,040	0,98	0,10	0,15	0,19	0,23	0,27
40	0,041	0,055	0,98	0,14	0,20	0,26	0,31	0,37
50	0,051	0,068	0,97	0,18	0,25	0,32	0,39	0,46
60	0,062	0,083	0,97	0,21	0,30	0,39	0,47	0,56
70	0,073	0,097	0,96	0,25	0,35	0,45	0,55	0,66
80	0,084	0,112	0,96	0,29	0,41	0,52	0,64	0,75
90	0,095	0,127	0,95	0,33	0,46	0,59	0,72	0,85
100	0,106	0,141	0,94	0,37	0,51	0,66	0,81	0,95
110	0,117	0,156	0,94	0,40	0,56	0,73	0,89	1,05
120	0,129	0,172	0,93	0,44	0,62	0,80	0,98	1,16
130	0,140	0,187	0,93	0,48	0,68	0,87	1,06	1,26
140	0,152	0,203	0,92	0,52	0,73	0,94	1,15	1,36
150	0,164	0,219	0,91	0,57	0,79	1,02	1,24	1,47
160	0,176	0,235	0,91	0,61	0,85	1,09	1,34	1,58
170	0,188	0,251	0,90	0,65	0,91	1,17	1,43	1,69
180	0,201	0,268	0,90	0,69	0,97	1,25	1,53	1,80
190	0,214	0,285	0,89	0,74	1,03	1,33	1,62	1,92

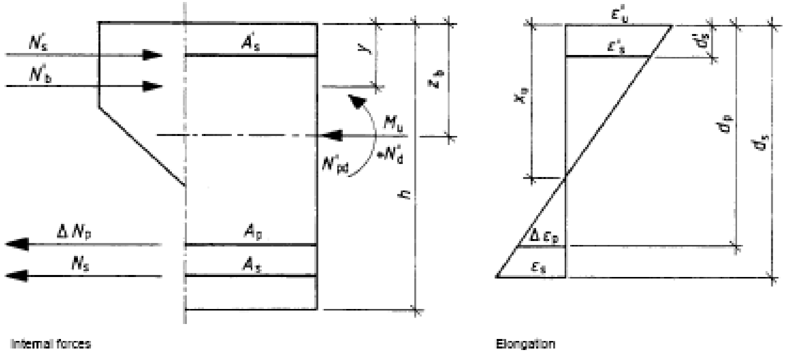
Bending moment and (prestressing) normal forces

The limit state involving bending and normal force is as follows:

$$M_d = M_u \quad \text{en} \quad N_d = N_u$$

in which:

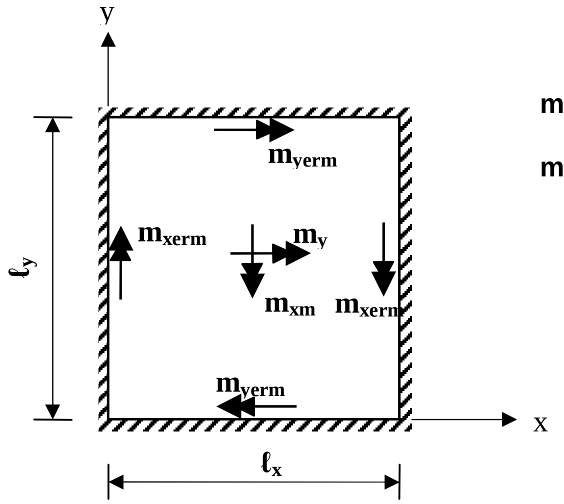
M_d = design value of the maximum occurring bending moment
M_u = maximum allowable bending moment
N_d = design value of the normal force
N_u = maximum tolerable normal force



$$M_u = (N'_{pd} + N'_d)(z_b - y) + \sum N_s(d_s - y) + \sum \Delta N_p(d_p - y)$$

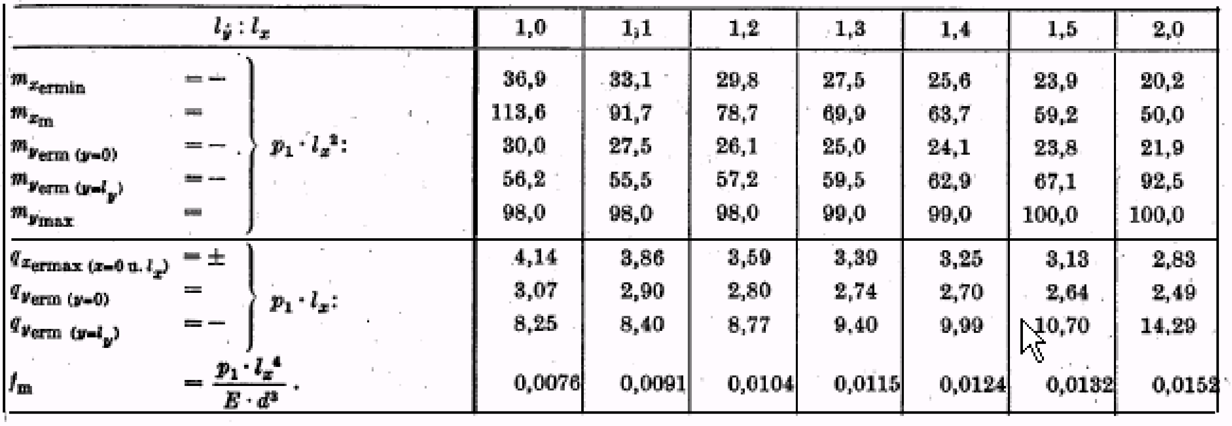
$$N_u = N'_b + N'_s - N'_{pd} - \Delta N_p - N_s$$

Plate bending moments m_x and m_y in kNm in a fixed supported slab along 4 edges with hydrostatic load (constant thickness)

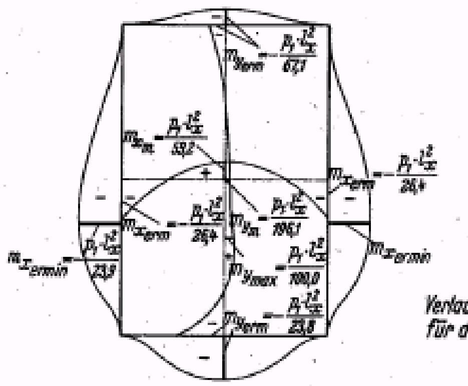


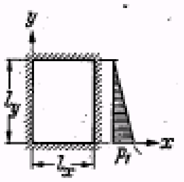
m_{xerm} m_{yerm} Fixed moments in the centre point on the edge

m_{xm} m_{ym} Span moments in the centre point of the plate

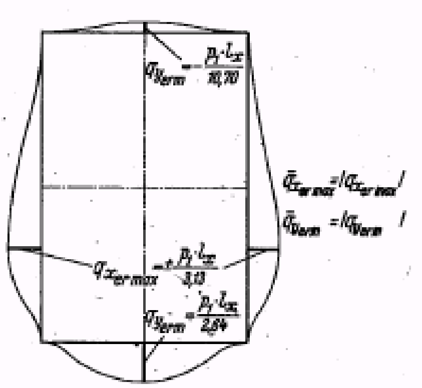


$l_y : l_x$			1,0	1,1	1,2	1,3	1,4	1,5	2,0
$m_{x_{ermin}}$	$= -$	$p_1 \cdot l_x^2 :$	36,9	33,1	29,8	27,5	25,6	23,9	20,2
m_{x_m}	$=$		113,6	91,7	78,7	69,9	63,7	59,2	50,0
$m_{y_{erm}\,(y=0)}$	$= -$		30,0	27,5	26,1	25,0	24,1	23,8	21,9
$m_{y_{erm}\,(y=l_y)}$	$= -$		56,2	55,5	57,2	59,5	62,9	67,1	92,5
$m_{y_{max}}$	$=$		98,0	98,0	98,0	99,0	99,0	100,0	100,0
$q_{x_{ermax}\,(x=0 \text{ u. } l_x)}$	$= \pm$	$p_1 \cdot l_x :$	4,14	3,86	3,59	3,39	3,25	3,13	2,83
$q_{y_{erm}\,(y=0)}$	$=$		3,07	2,90	2,80	2,74	2,70	2,64	2,49
$q_{y_{erm}\,(y=l_y)}$	$= -$		8,25	8,40	8,77	9,40	9,99	10,70	14,29
f_m	$= \dfrac{p_1 \cdot l_x^4}{E \cdot d^3} \cdot$		0,0076	0,0091	0,0104	0,0115	0,0124	0,0132	0,0152





Verlauf der Schnittgrößen für das Seitenverhältnis $l_y : l_x = 1,5$



Moment diagrams for $l_y / l_x = 1,5$

Shear force diagrams for $l_y / l_x = 1,5$

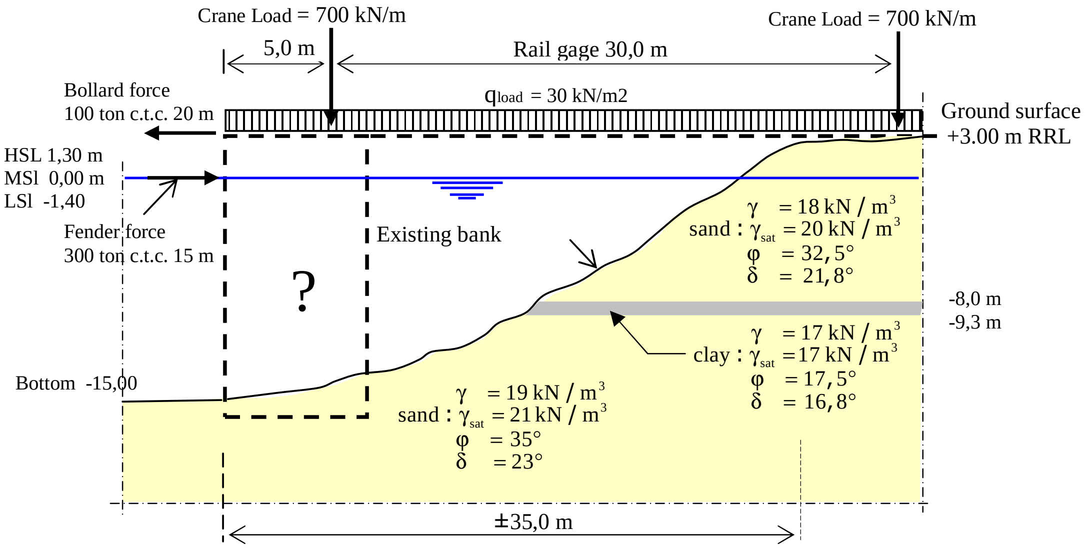
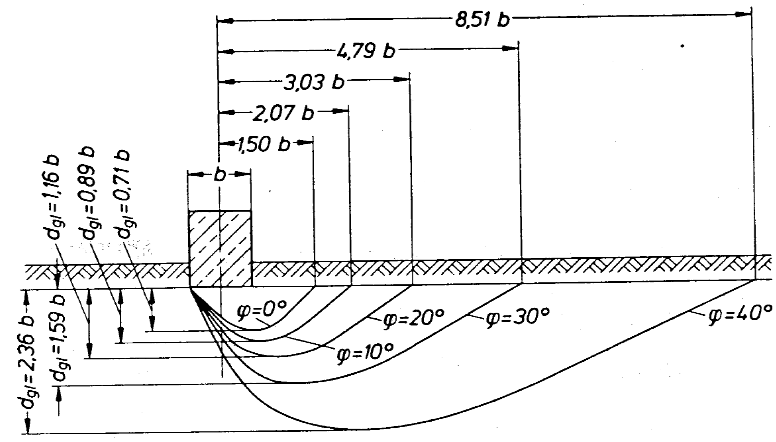


Fig.3 Existing situation with soil profile and "To Be" situation including loading conditions



Bearing capacity depends on width of footing