A Comparison between Circular Cell Cofferdams and Double Wall Cofferdams and different Loads by Means of a Simple Calculation Scheme

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HISTORICAL ABSTRACT OF COFFERDAMS DEVELOPMENT

The using of cofferdams nearby rivers to protect building pits against peak discharges is part of the history in development of soil-mechanical engineering. The roman architect POLIO VITRUVIUS has already written about it in his well-known book „De Architectura" 25 years before Christ was born. Phoenizien and roman harbour engineers have built cofferdams like shown in fig.1 in the antike periode in the eastern part of the mediterenean sea.written about it in his well-known book „De Architectura" 25 years before Christ was born. Phoenizien and roman harbour engineers have built cofferdams like shown in fig.1 in the antike periode in the eastern part of the mediterenean sea.

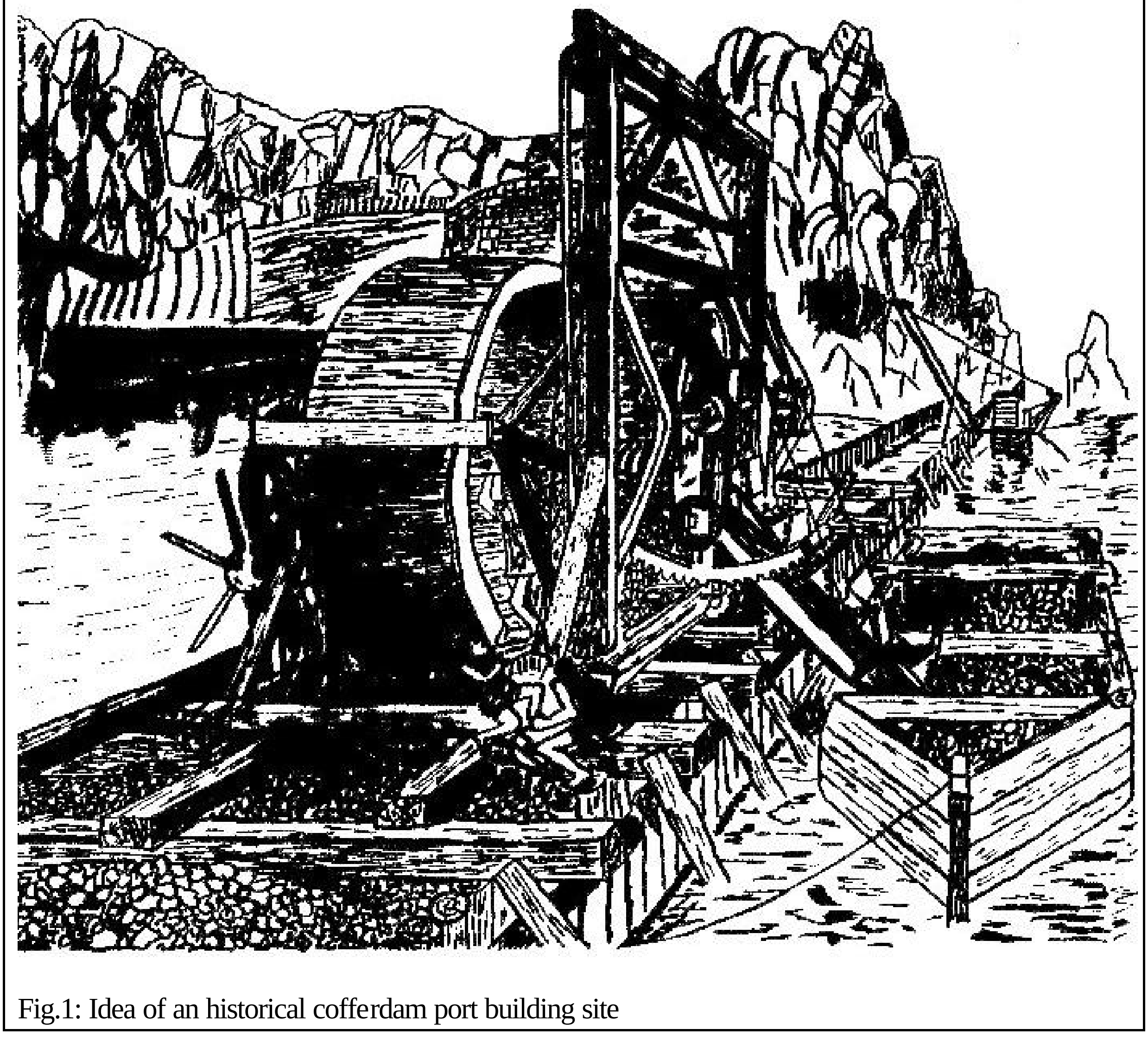


Fig.1: Idea of an historical cofferdam port building site

Modern cofferdams were possible with the development of the steel-sheet-pile at the beginning of the 20th. century. To roll the steel-sheet-pile together with the lock makes sure the birth of Circular-Cell-cofferdams.

Today cofferdams with a total height up to 25 m and a width up to 30 m and more are to be built as a part of quay-walls in modern marine terminals. In Germany most used is the double-wall-cofferdam-type (DWC), but in other parts of the world very often is used the circular-cell-cofferdam-type (CCC).

The advantage of the CCC is a very small penetration depth under the future sea or harbour bottom. The DWC most is used in cases, when only a short length of a quay-wall or a building-pit side is to be built.

CUSTOMERY USED CALCULATION SCHEMES

The calculation methods for these high specialised constructions are world-wide very different. The methods of JELINEK (Germany), KITAJIMA (Japan), TVA (USA) and CUMMINGS (USA, UK) to estimate the cofferdam's dimensions are most used.

The goal of all calculations is to minimize the dimensions of the cofferdam and in consequence of this, the costs of the quay wall. German soil-mechanical engineers normally use a calculation scheme under modifying the methods of JELINEK and OVESEN.

The essential part of this scheme is a rupture within the filling of the cofferdam with a field of rupture-lines over a bended sliding line. This sliding line can be destinated as a logarithmical-spiral with the form $r = a \cdot e^{c \cdot \tan j'}$. See more about this logarithmical spiral in figure 2.

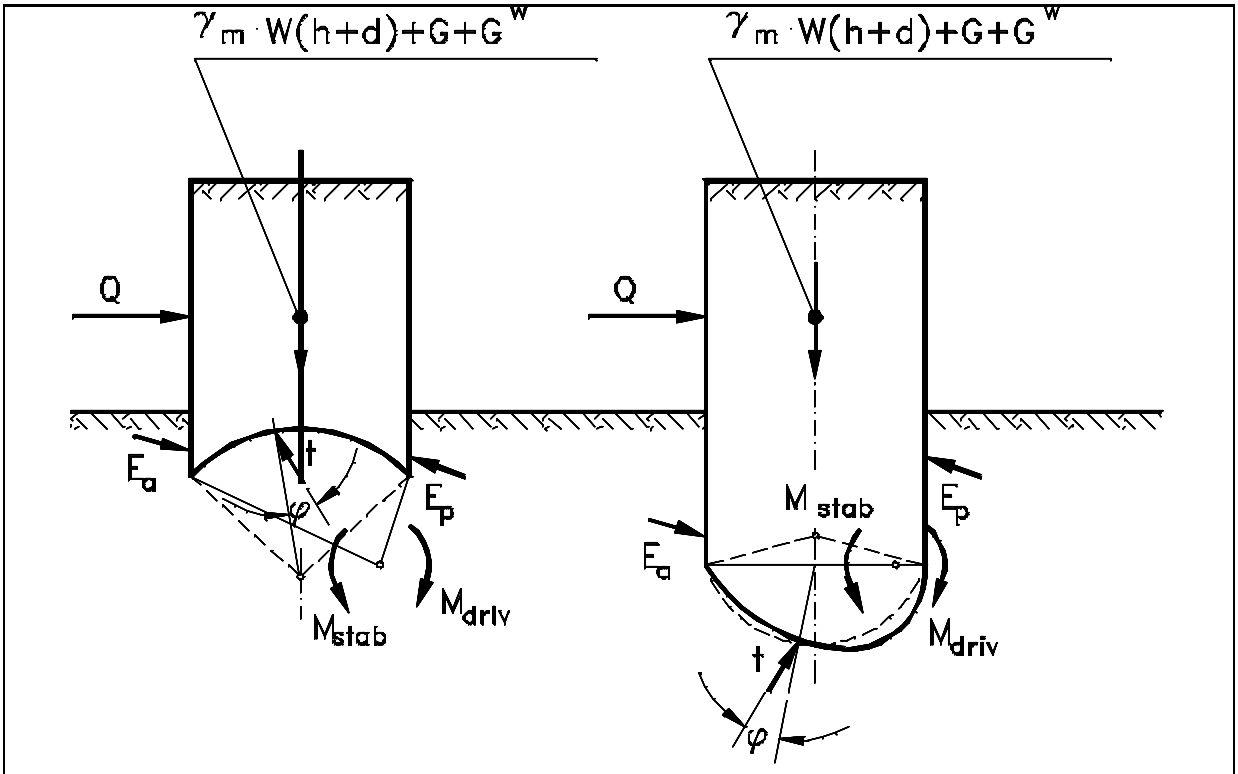


Fig.2: Filling rupture over a logarithmical spiral as given by OVESEN

Make use of this method for the planning of several quay-walls it was found out that there are some differences in calculation between cofferdams used as protection elements against discharges and cofferdams used as quay walls with a very complex load of different dynamic influences.

Figure 3 gives an idea of the geometrical correlations between the logarithmical spiral and and the cofferdam.

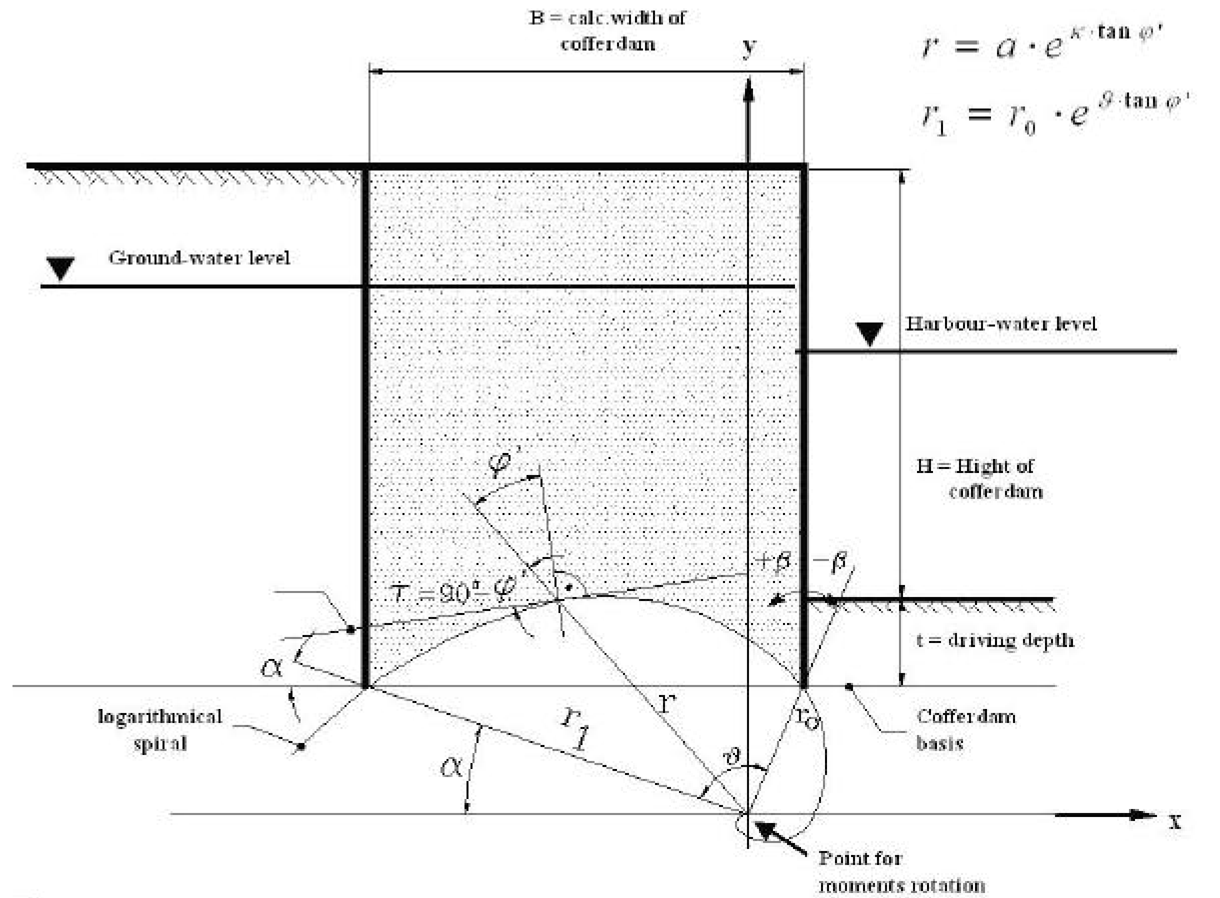


Fig. 3: Geometric details of logarithmic spiral

To look to OVESENS modell-tests and to make own theoretical experience it was found out, that there isn't any translation of the cofferdam, but only a rotation around the extraction of logarithmical spiral. If this will happen, no passive earth pressure cannot be active. The distribution of passive earth-pressure cannotbe triangular it must be a parabolic load picture.

A SINGLE METHOD FOR SOIL-MECHANICAL COFFERDAM CALCULATION

Under this goal a new calculation scheme for circular cell cofferdams was developed. Under use this scheme some correlation's were found out between the different kinds of load and the dimensions of the cofferdam in a uniform soil. Some diagrams have been developed, which allow the user to estimate the width of a cofferdam by given height, different loads and different soil conditions. In figure 4 are given the boundary elements, which were the basis for the diagrams.

Several equations as the result of the comparison

Each cofferdam-section is characterized by its dimensions, especially by the height and the width. So the quotient *H/B* can be called form-factor. Without any loads, only live load and earth-pressure by the same water-level before and behind the quay-wall, each form-factor must give nearly the same safety against a rupture of cofferdams filling by different dimension.

Each load reduces the safety against sliding on the logarithmic spiral by factor y_i, called the loading-factor. Different loads can be joined together, because the law of superposition is valid. The result of this calculation is the load-product Y. So it is possible, to calculate by a modified safety the required form-factor *H/B*.

Because the result is not sufficient due to little and heavy loads and the height of the cofferdam a correction of the founded result is necessary. Two correction-factors Q_1 and Q_2, which are graphically overlapped to one factor Q, must be used to find a content solution. The different factors can be given in the mathematical form:

Formula to calculate the cofferdams width:

$$B = \frac{H}{a_{(j')} \cdot h_{kontr}^{\;b_{(j')}}} \cdot \frac{\Theta_2}{\Theta_1}$$

herein are:

Form-factor:

$$\frac{H}{B} = a \cdot h^b$$

Load-factors:

$$y_q = a_q + b_q \cdot P_q + c_q \cdot P_q^2 + d_q \cdot P_q^3$$
$$y_{wü} = a_{wü} + b_{wü} \cdot w_ü + c_{wü} \cdot w_ü^{\,2} + d_{wü} \cdot w_ü^{\,3}$$
$$y_t = a_t + b_t \cdot t + c_t \cdot t^2 + d_t \cdot t^3$$
$$y_H = a_H + b_H \cdot P_H + c \cdot P_H^2 + d \cdot P_H^3$$
$$y_V = a_V + b_V \cdot P_V + c \cdot P_V^2 + d \cdot P_V^3$$

First correction-factor:

$$\Theta_1 = a_1 + b_1 \cdot \frac{H}{\Psi} + c_1 \cdot \left(\frac{H}{\Psi}\right)^2 + d_1 \cdot \left(\frac{H}{\Psi}\right)^3 + e_1 \cdot \left(\frac{H}{\Psi}\right)^4 + f_1 \cdot \left(\frac{H}{\Psi}\right)^5 + g_1 \cdot \left(\frac{H}{\Psi}\right)^6$$

Second correction-factor:

$$\Theta_2 = a_2 + b_2 \cdot \frac{H}{\Psi} + c_2 \cdot \left(\frac{H}{\Psi}\right)^2 + d_2 \cdot \left(\frac{H}{\Psi}\right)^3 + e_2 \cdot \left(\frac{H}{\Psi}\right)^4 + f_2 \cdot \left(\frac{H}{\Psi}\right)^5 + g_2 \cdot \left(\frac{H}{\Psi}\right)^6$$

There are several constants in the formulas above. This constants are necessary to describe different soil-mechanical criteria’s like the angle of internal friction, cohesion and the unit weight of soil of a homogeneous cofferdam filling and backfilling.

For six different kinds of soil are this formulas analysed. This are:

Nr.	Angle of internal friction *j* ‘ (°)	Angle of wall friction *d* (°)	Unit weight of soil g'/g_a' (KN/m³)	Cohesion *c’*(KN/m²)
1	25.0	0	18/9	25
2	27.5	0	18/10	10
3	27.5	2/3 *j* ‘	18/10	0
4	30.0	2/3 *j* ‘	19/10	0
5	32.5	2/3 *j* ‘	19/10	0
6	35.0	2/3 *j* ‘	19/10	0

The result is drawn down in seven diagrams, which can be used for cofferdam calculation. They are given with an example at the end of this paper. The diagrams was approved by a lot of different cofferdam sections with variable loads and dimensions. It was seen, that the medium of all calculations has had an exactness of nearly 99,9 %. There were 80% of all results, which gave an approximated width between 98% and 102% of the exactly calculated width, and another 20% gave a width between 96% and 104%.

To estimate in a short quick form the width of a cofferdam, used as quay wall the using of the diagrams can be recommended.

A COMPARISON BETWEEN SEVERAL CALCULATION METHODS

The comparison of the results for some circular-cell-cofferdam cross-sections by application the new calculation scheme and the diagrams with the result, won by using other calculation methods are sufficient. A cofferdam section filled and backfilled by soil nr.4 (*j* ‘ = 30°) was tested under using the methods of JELINEK, KITAJIMA and DISMUKE/CUMMINGS. A water pressure between harbour water level and groundwater level of 30 KN/m² and a surface load of 40 KN/m² behind the quay wall were given. For seven different heights the calculation was done Find the result in fig.5.

It is interesting, that the method of KITAJIMA gives the largest width of a cofferdam. This must be put down to the fact, that this method don’t uses the penetration depth of sheet-piles under the harbour bottom for the calculation.

CIRCULAR-CELL-COFFERDAM - DOUBLE-WALL-COFFERDAM WHAT ARE THE DIFFERENCES?

The method for a simple calculation of cofferdam-filling rupture was developed before the background of circular-cell-cofferdams. But the found-out rupture mechanisms also can apply to the double-wall-cofferdam. There is no difference in soil-mechanical regard of the filling and its surrounding than the three-dimensional development of the rupture in case of a circular cell. But idealized also the CCC can be seen as a line-building.

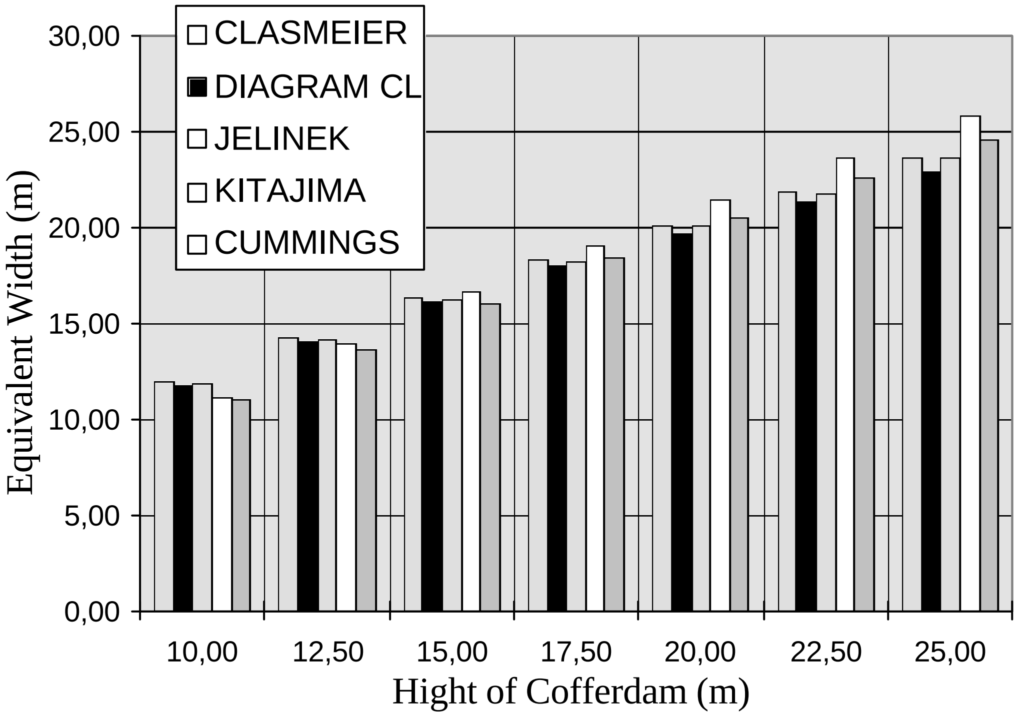


Fig.5: Comparison of circular-cell cofferdam's width calculated by several methods

But nevertheless are there some differences of importance for the calculation and to build circular-cell-cofferdams and double-wall-cofferdams.

Circular-cell-cofferdam

The fact, that the CCC is able to admit ring pull forces allows to minimize the penetration depth. Only the safety against base failure gives this depth. Normally it is around 10% to 20% of cofferdams height. So the width can be calculated as a function between filling rupture and base failure.

The CCC is very easy to install, if heavy-load floating cranes are available. The cell its to prefabricate nearby the quay-wall site and than to float to destination-point. The cells weight is not very high, because the steel-sheet-pile and the sheet-pile lock are able to admit strong forces. The cell can be set up to the sea-bottom and then be driven by vibrators to calculated depth. Filling the cell and backfilling are the next steps. There are no intermediate steps, that failing must be feared.

Double-wall-cofferdam

Characterized for the double-wall-cofferdam is the using of an endless sheet-pile wall at each side. This sheet-pile is to drive very deep below the bottom. At first to withstand currents and waves but, at second to give enough driving depth to activate passive earth pressure to make balance to active earth pressure between the two diaphragms. If this balance is not guarantied it is not possible for the cofferdam to withstand another earth pressure at the back.

Normally in subordination of one, two or three layers of horizontal anchoring the penetration depth of DWC is between a third and a fourth of cofferdams height. Due to the fixation of steel sheet-pile in the underground and to withstand the connected bending moment very solid steel-profiles are needed.

To build a DWC however don't require heavy load floating cranes. Only a pontoon installed with a piling rig is necessary. But a lot of fitter-work is to be done for all connections and joints between steel-sheet-pile and anchoring.

The decision between CCC and DWC is not easy. Therefore it is helpful to have some more information about needed steel weight, driving surface under the sea-bottom and the driving depth. The fitter work can be estimated about the experience of used steel for horizontal anchoring by a double-wall cofferdam. For the circular-cell-cofferdam a so called driving desk, which is used to prefabricate the cell before floating-crane comes, is to calculate. Two driving desks normally are sufficient.

To give this help for the same load and the same height of a quay wall a comparison was made between CCC and DWC.

COFFERDAM TESTING MODEL

Like before a cofferdam cross-section was chosen with a normal load and an ordinary filling. Five different cofferdam height between 10 m and 20 m were investigated. The water pressure has had an value of 40 KN/m² and the back surface load was 20 KN/m².

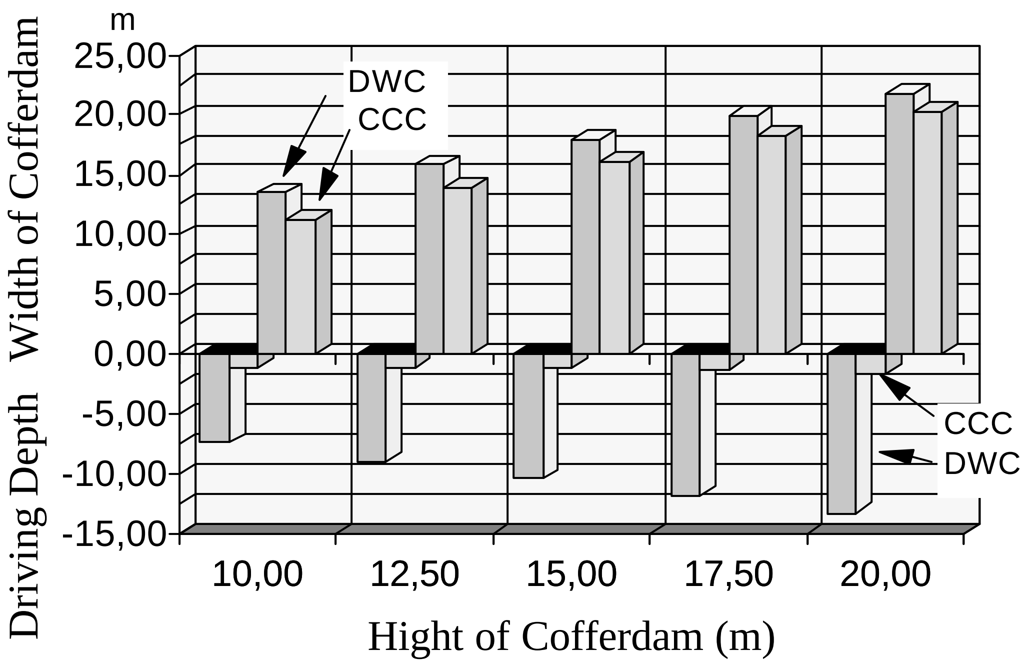


Fig.6: Differences between driving depth and width of circular cell- and double wall cofferdams

The driving depth was calculated in a first step by the requisite safety against base failure. This depth was enough for circular cell cofferdams calculation against filling rupture. For CCC the driving depth and the width were fixed. The driving depth of DWC was calculated by the sheet-pile calculation scheme of BLUM. The driving depth was sufficient for the safety against base failure, but the safety against filling rupture needs to lengthen cofferdam's width.

All results are given in fig.6. It is shown that CCC's driving depth rises from 1.15 m to 1.55 m and DWC's driving depth from 7.41 m to 11.94 m.

So it is not amazing that the driving surface of the circular-cell cofferdam its only a fraction of steel-sheet pile which are driven down by double-wall cofferdams. Nevertheless the total Diaphragm surface of the CCC is more than in case of DWC.

Driving energy is more than four times higher by DWC, not only due to the surface also due to the steel-sheet-pile weight. The needed steel-sheet-pile profile for CCC is given by a weight of 141,00 kg/m², but the profiles for double-wall cofferdams are given by a weight from 200 kg/m² up to 354 kg/m². Here are heavy profiles necessary, even for higher cofferdams combined double-H-profiles with Z-profiles.

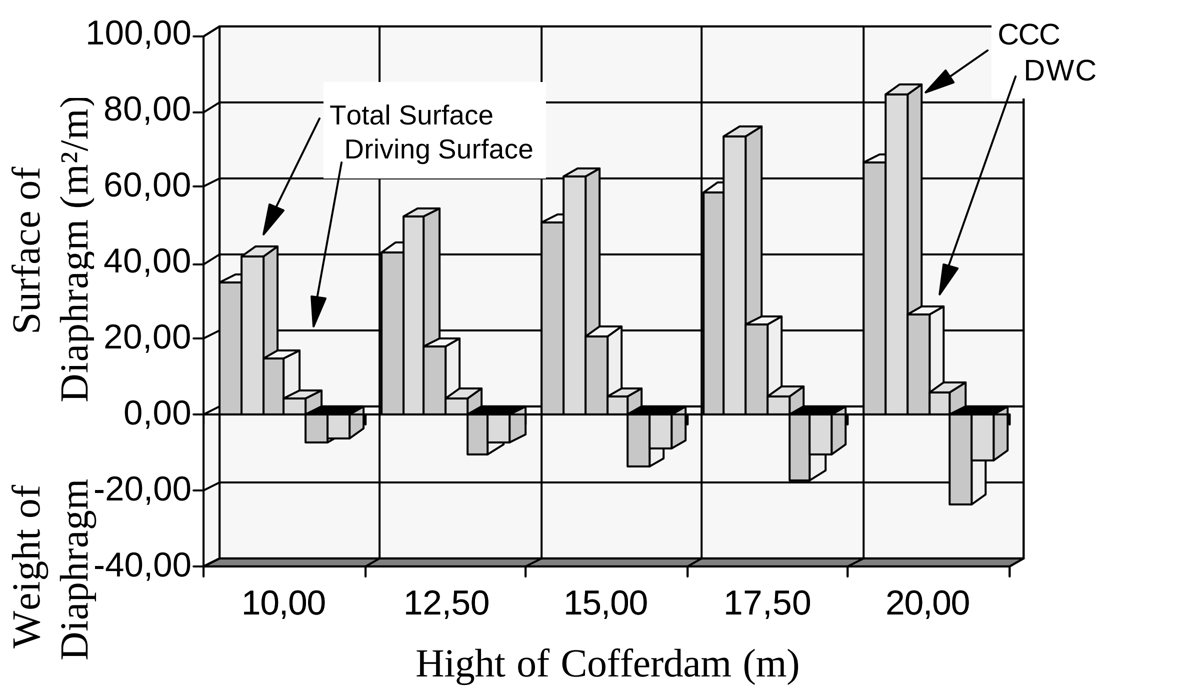


Fig.7: Difference between Diaphragms surface and weight of circular cell- and double wall cofferdams

Fig.7 gives an impression that normally the circular-cell cofferdam must be preferred. Especially when a longer quay wall is to be built, the saving of driving energy and steel and therefore also energy for steel production gives aside the economical advantage a high ecological advantage of CCC against DWC. Simple installation of circular-cell cofferdam gives another advantage against the employment of high specialized fitter-man for anchoring sheet-piles at double-wall cofferdam. As a whole the CCC has the best conditions for an use in quay wall building in European ports and also like in ports all over the world.

Nevertheless the DWC is an important element in port construction, when there are only small quay walls to build. In each case the harbour engineer has to calculate his quay wall and only he has to decide, what is the best solution. For this decision the preceded reflection are made. May be they will be in future a little help in port planning and construction.

A GUIDE FOR USING THE CALCULATION DIAGRAMS

The using of the diagrams to estimate very quickly the width of a cofferdam by a given load and quay wall height is very simple. There a seven diagrams, five for the load factor, on for a correction factor and one for the form factor *H/B*.

<u>An example is given with the following quay wall:</u>

Height of quay wall	H = 17,50 m
Kind of soil	j' = 30°
Harbour water level	HWL = 5,00 m
Back surface load	P_q = 40 KN/m²
driving depth	t = 2,00 m
Safety factor	h = 1,5

<u>**Step 1:** Find the load-product *Y*</u>

From y - Diagram:
Load-factor y_q = 0,748 from diagr.3
Load-factor $y_{wü}$ = 0,677 from diagr.4
Load-factor y_t = 0,804 from diagr.5
Load-factor y_H = 1,000 from diagr.6
Load-factor y_V = 1,000 from diagr.7

Load-product: $\Psi = y_q \cdot y_{wü} \cdot y_t \cdot y_H \cdot y_V$
= 0,749*0,677*0,904*1,0*1,0 = 0,458

<u>**Step 2**: Find the correction-factor *Q*</u>

Quotient: $\frac{H}{\Psi} = \frac{17{,}50}{0{,}458} = 38{,}21 \Rightarrow \Theta = 0{,}907$

go to diagram 2 and look for *H/Y*

<u>**Step 3:** Calculation of improved safety factor h_{kontr} and quotient *H/B*</u>

improved safety factor $h_{kontr} = h \cdot \frac{1}{\Psi}$ = 1,5/0,458 = 3,27

Look to diagram 1 and find form-factor *H/B* = 0,951

Step 4: Determining of cofferdam width

With the calculated and founded data’s cofferdam’s width now is to ascertain.

$$B = \frac{H}{\left(Bw\dfrac{H}{B}\right)} \cdot \Theta = \frac{17{,}50}{0{,}951} \cdot 0{,}907 = 16{,}68m$$

$\left(Bw\dfrac{H}{B}\right)$ means the form factor found out in diagram 1.

An exactly calculation under using the described method gave as a result a cofferdam width of B = 16,74 m. The diagrams can be recommended to soil mechanical calculation of coffer-dams.

CALCULATION DIAGRAMS

Diagram nr.1 for form-factor *H/B*

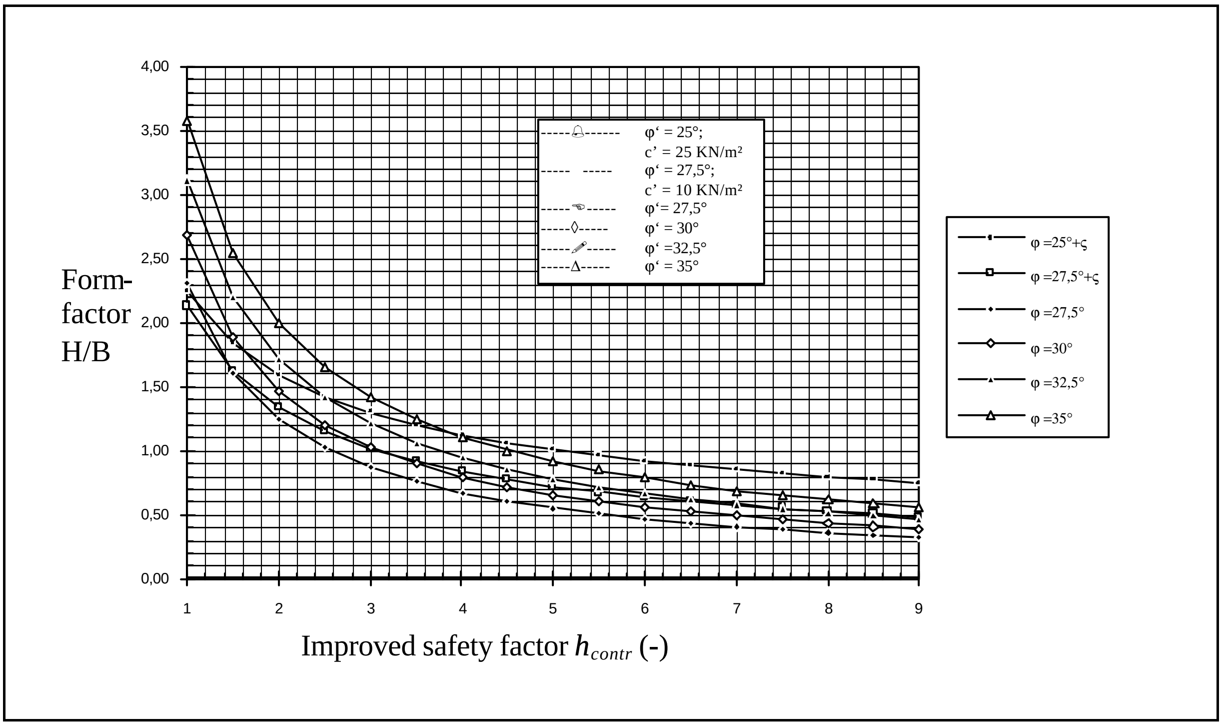


Diagram nr.2 for correction-factor Θ

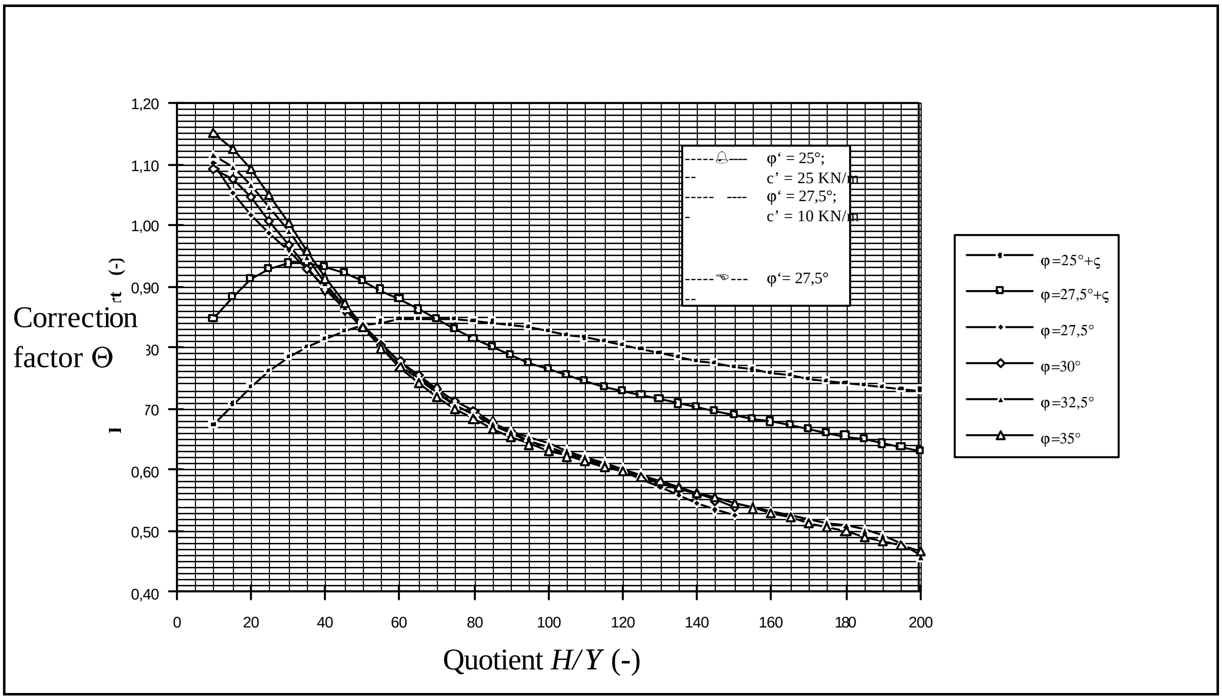


Diagram nr.3; Load-factor for back surface load y_q

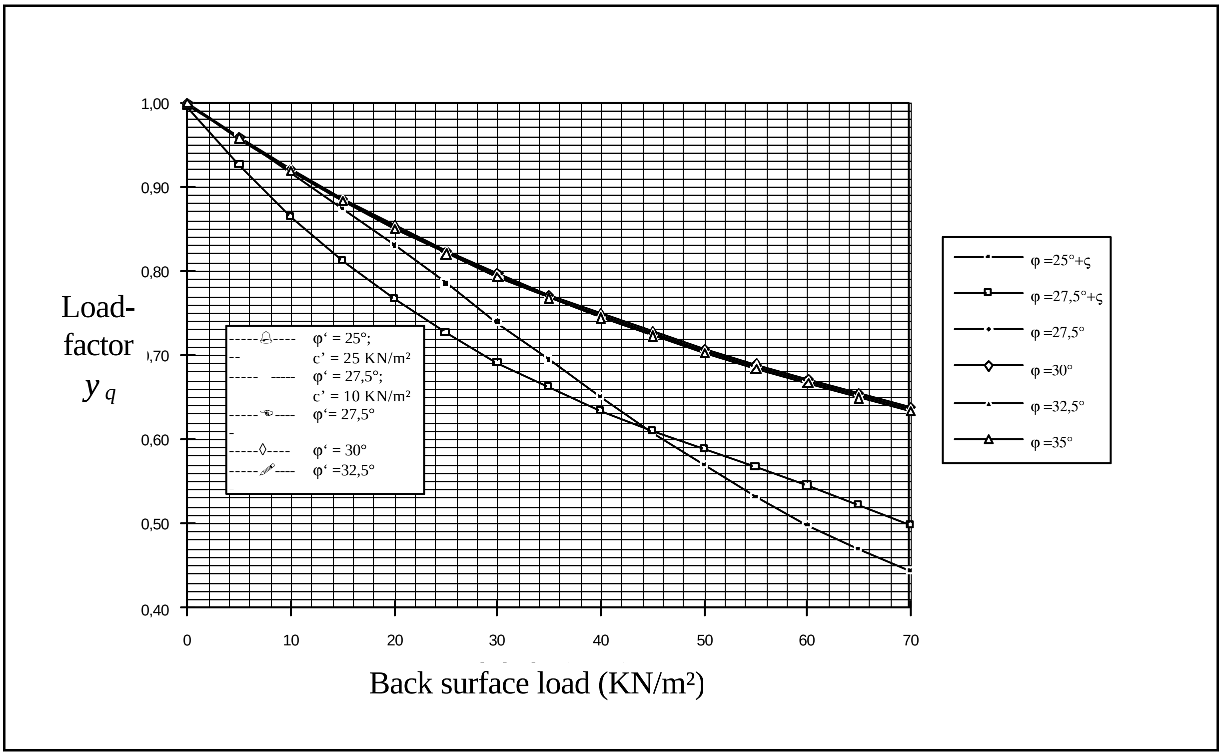


Diagram nr.4; Load-factor for water pressure $y_{wü}$

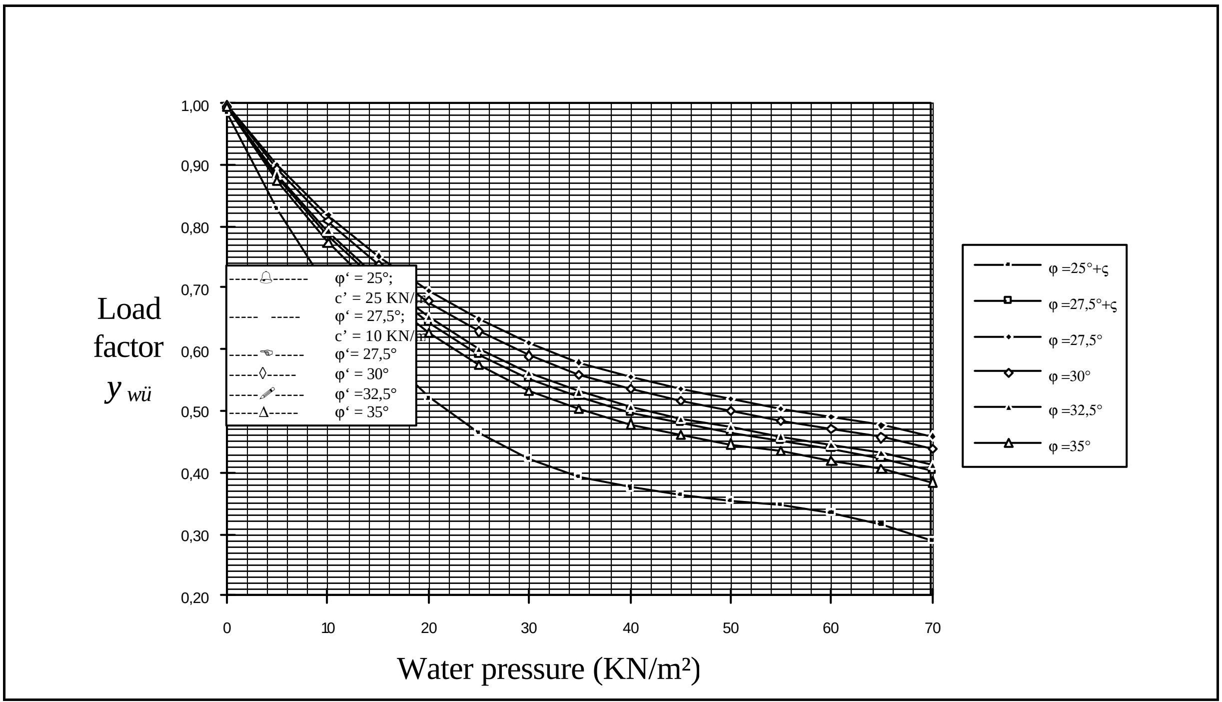


Diagram nr.5; Load-factor for driving depth y_t

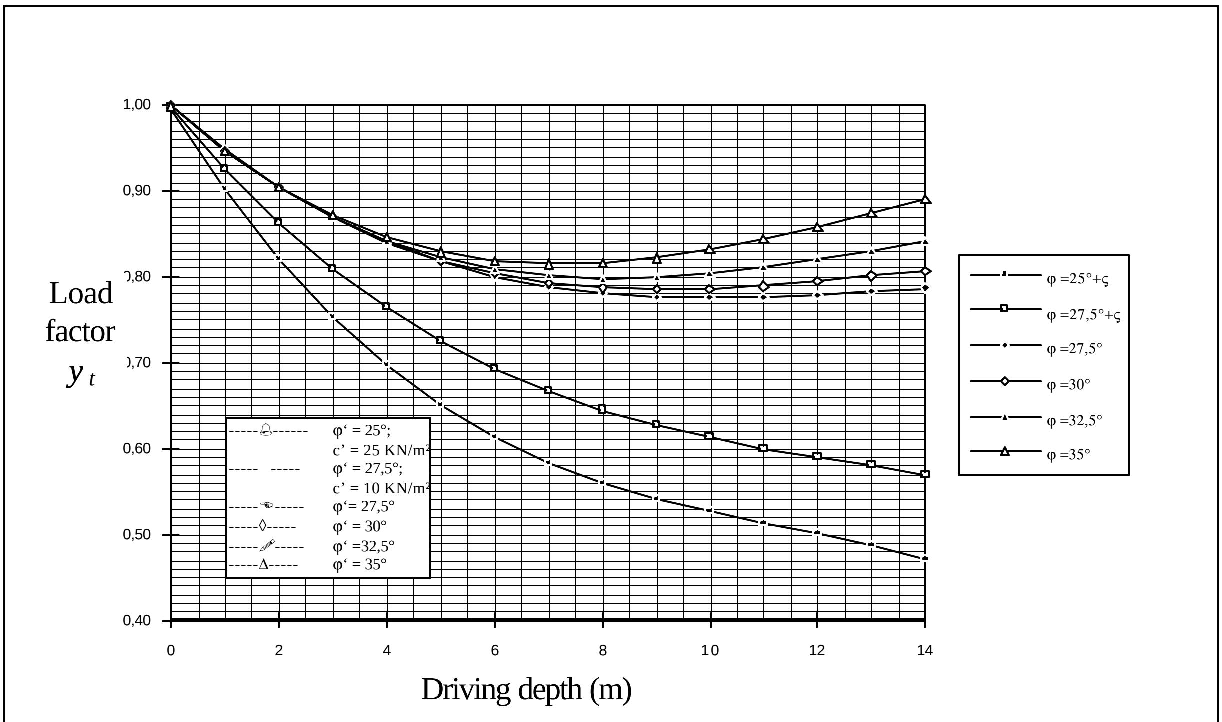


Diagram nr.6; Load-factor for horizontal head force y_H

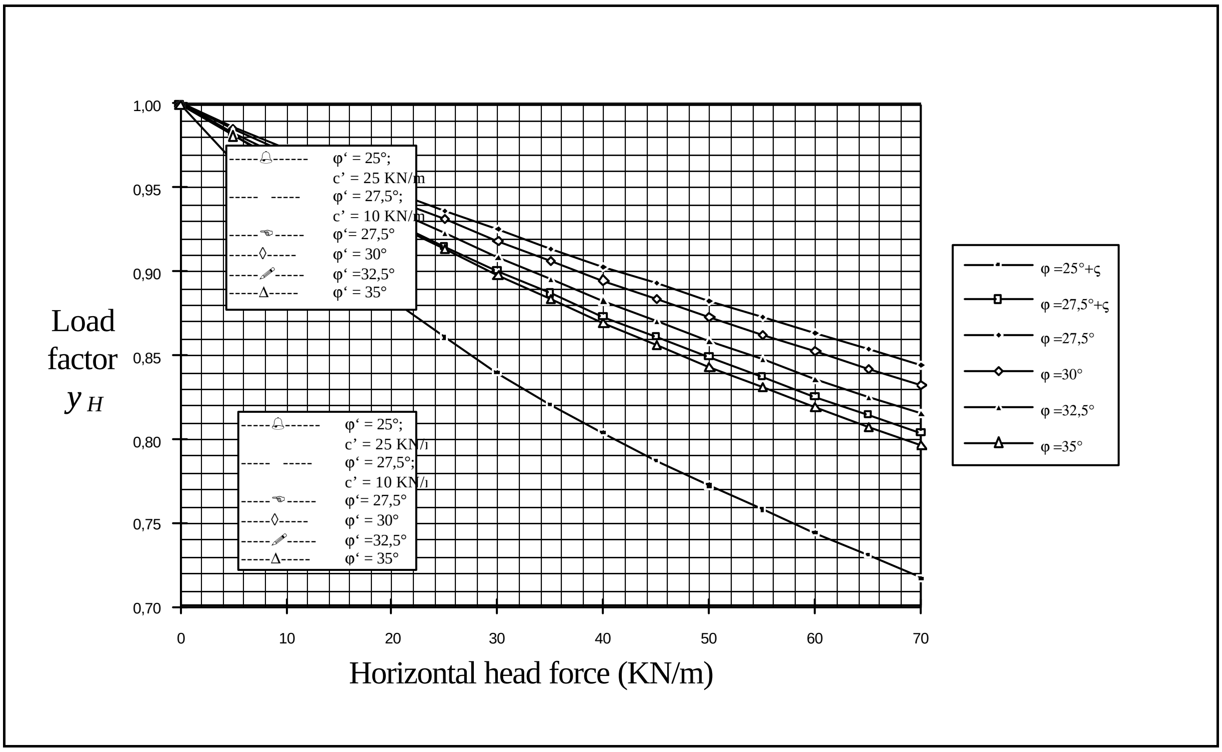
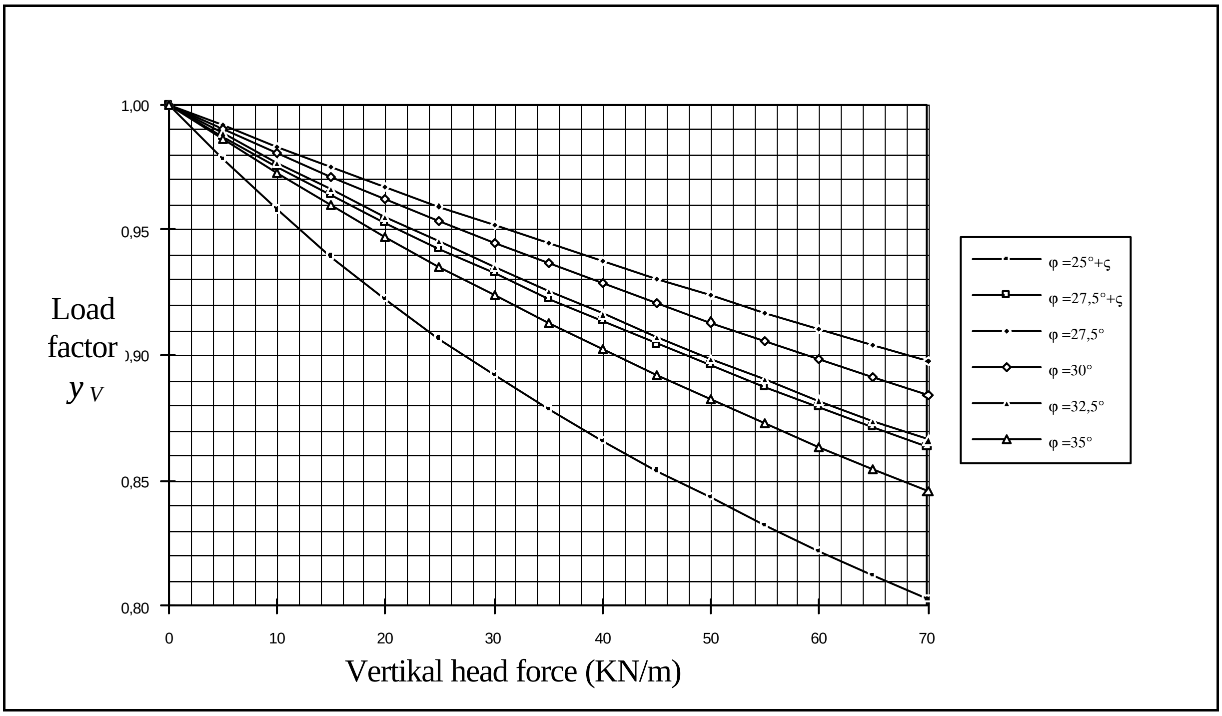


Diagram nr.7; Load factor for vertical head force y_V



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