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THE CONSTRUCTION COST OF QUAY WALLS

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This paper is part of a study on port economics (1). In view of the recommendation of the EEC transport comittee it is of the utmost importance that EEC-ports operate with fair competitive principles. Therefore, pricing and investment rules for ports must be found. Although there is much criticism on the policy rules for public enterprises, derived from the theory of welfare economics (2), better substitutes are not available. In order to apply these criterions, port authorities must have complete information on costs. Therefore, a major part of this research is concerned with port costs. In this paper we deal with the construction costs of quay walls. In the first section of this paper different types of quay walls are briefly described. Secondly, the data material on which this analysis is based, is discussed. Thirdly, a regression analysis is performed. In the final section, some tentative conclusions are drawn concerning further use of the results for port planning.

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(1) Project of NFKWO, nr. 764.

(2) See NATH, S.K., A reappraisal of welfare economics, London, 1969, p. 163-166.

1. DIFFERENT TYPES OF QUAY WALLS

Several fairly similar definitions of quays and wharves are available. According to AAPA (1) "... a wharf is a structure extending parallel with the shore line, connected to the shore at more than one point (usually with a continuous connection) and providing, in most cases, berthing at the outshore face of the structure only ...". This definition also includes, besides quay walls, jetties and piers. In this paper we use a rather limiting definition following Bertlin and Partners (2): "... we define quay walls to include any berth structure which provides an uninterrupted surface from the cope to land behind the quay ...". So jetties and also open construction wharves running parallel to and not continuously connected to the shore are excluded from this analysis.

A first classification of quay walls is based on the mode of foundation, which depends directly on the soil conditions (3). To main types can be distinguished viz. quay walls with a continuous foundation and those with a discontinuous foundation. Quay walls with continuous foundation are applied when the level of the soil with "good" characteristics (4) is at a small distance of the level of the harbour bed. However, when the distance between the existing bed level and the level of "good" soil is large, discontinuous foundation is required. The construction is then built on piles driven till they are in "good" soil. It is obvious that the design of a quay wall is highly influenced by the ground conditions of a particular site. Therefore, a particular design is to a degree representative for soil conditions. In studying cost relations, soil conditions are dealt with, when different types of design are distinguished.

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(1) American Association of Port Authorities, Port Design and Construction, Washington, 1964.
(2) Bertlin and Partners, Port Structures, National Ports Coundil, London, 1970.
(3) Cfr. J. CHAPON, Travaux Maritimes, Tome II, Chapitre XI, Ouvrages d'accostage, p. 75.
(4) "good" soil means that a pressure of more than 10 t/m^2 is sustained. See footnote 3.

In order to make a reasonable use of the available data in a regression analysis, we distinguish four different types of design viz. (figures in appendix i)

1. anchored sheet pile walls and
   sheet pile walls with relieving platforms
2. open piled constructions
3. concrete walls
4. miscellaneous types.

Anchored sheet pile walls (fig. a in appendix i) consist of a - usually steel - sheet pile wall and an anchorage system. The latter includes the anchors - A-frame of piling, steel piling, concrete, ... - and one or more tie-rods connecting the upper part of the sheet pile wall and the anchors. Sheet pile walls with relieving platforms (fig. b) are similar to anchored sheet pile walls. Instead of tie-rods, a platform supported on piles or concrete, sustains the sheet pile wall.

Open piled constructions (fig. c) - which are of discontinuous foundation - are of a great variety, depending on particular soil conditions. With this type, a suspended deck is supported by an open piling structure. As indicated before these constructions are applied especially where ground conditions are poor.

Concrete walls (fig. d) are either massive or in blocks. They can be built in the dry or in the wet. This type of wall is very solid and can stand for long periods.

The last group indicated as "miscallaneous types" includes monoliths (fig. e) and other designs meeting particular site conditions, which do not fit into the previous categories.

Although this variety of construction types it is useful to derive a set of construction cost equations in order to explain a part of the variance in quay wall cost. So, in planning quay wall constructions uncertainty about costs can be reduced.

2. THE DATA

The data used in this analysis are drawn from a previously mentioned study of Bertlin and Partners (1). In this research different physical data on 65 quay walls throughout the world are gathered. For 61 of these quays a complete set of physical parameters and cost data are available.

For each quay wall the following characteristics, besides the port and the name of the quay, are known:

1. type of construction
2. construction period
3. actual cost (in £/m run of quay)
4. cost adjusted to 1968 (in £/m run of quay)
5. height of the cope above dock bed (in m)
6. superimposed uniformly distributed loading on the quay (in t/sq.m)
7. tidal range (in m)
8. width of the apron included in the cost (in m)
9. length of quay constructed (in m)

Bertlin and Partners consider eight types of construction (2) viz. 1° anchored sheet pile walls - single tie (10); 2° anchored sheet pile walls - two ties (2); 3° pile walls with relieving platform (23); 4° open piled construction with suspended slab (9); 5° concrete walls built in the dry (4); 6° concrete walls placed in the wet (6); 7° monoliths (2); 8° miscellaneous (5). For the classification of the present analysis we have grouped the first three classes into "sheet pile walls " (35), class 5° and 6° into

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(1) See footnote 2 p. 2.

(2) The figures between brackets after the types are the numbers of observations. Only these quay walls are included with a full set of parameters.

"concrete walls" (10), and class 7° and 8° into "miscellaneous constructions" (7). The other group viz. "open piled constructions" (9) remains the same as in the Bertlin study.

The actual cost of non-British constructions are converted into equivalent sterling costs. By weighting the sterlingcost with a compound index of construction prices the cost adjusted to 1968 in sterling was obtained (1).

The other data parameters are quite obvious.

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(1) See, Bertlin and Partners, o.c., Vol. II, p.2-3.

3. THE REGRESSION ANALYSIS

In the second section of this paper we saw that the sample sizes of the last three groups (open piled; concrete walls and miscellaneous) range from 7 to 10 observations. For these small samples it is impossible to include five independent variables viz. height, apron width, length, tidal range and loading. Before estimating construction cost equations for these separate types of quays the set of determining variables must be reduced to the most important variables. Therefore, this section starts with equation estimates on the pooled data; next, equations for different types of construction will be derived. For sheet pile walls (35 observations) a regression with five independents might be reasonable.

3.1. Cost-equations on pooled data

The first estimated equations does not take into consideration the type differences. This "mean-cost-function" is

$$C_i = f.H_i^a W_i^b L_i^c U_i^d e^{T_i} E_i \qquad \text{(a.I)}$$

where C = adjusted cost in sterling per metre run of quay

H = height (in m.) of the cope above dock bed

W = width of apron (in m.) included in the costs

L = total length constructed (in m.)

U = the superimposed uniformly distributed loading (in t/sq.m)

T = tidal range in m.

a,b,c,d,e,f = parameters

E = disturbance

Total costs are therefore equal to

$$TC_i = f.H_i^a W_i^b L_i^{c+1} U_i^d e^{T_i} E_i$$

Instead of estimating the total construction cost function, we prefer "mean-cost" estimates (i.e. cost per metre run), otherwise, the effects of other variables than length would probably be lost. The function is not logarithmic for tidal range. Some quay walls in the sample are constructed in non-tidal docks so that the tidal range becomes zero in these cases.

The estimate of the neperian logarithm of equation (a.I) gives the following results (1)

$$\log C = 3.405 + \underset{(0.313)}{1.368} \log H + \underset{(0.051)}{0.159} \log W - \underset{(0.052)}{0.053} \log L + \underset{(0.130)}{0.062} \log U + \underset{(0.034)}{0.015}\, T$$

$n = 61$
$R = 0.67 \quad \bar{R}^2 = 0.40$
$F(5,55) = 8,97$

From this equation we analysed the residuals in order to see if the normality conditions is fullfilled and to investigate differences between the types of construction.

The residuals are plotted on a histogram with their ranking number. The first 35 observations are obviously overestimated in this regression analysis.

Therefore we proceeded with the same equation after introducing dummy variables for the type of construction.

This results in the following equation (2):

$$C_i = f_1 f_2^{X_2} f_3^{X_3} f_4^{X_4} H_i^a W_i^b L_i^c U_i^d e^{T_i} E_i$$

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(1) The figures between brackets below the coefficients are the standard errors; n = number of observations; R = multiple correlation coefficient; $\bar{R}$ = corrected R for degress of freedom; F = F-value of regression.

(2) For symbols see p. 5.

with X_2 = 1 for open piled construction
0 for all other types
X_3 = 1 for concrete walls
0 for all other types
X_4 = 1 for miscellaneous constructions
0 for all other types.

The estimate gives

$$\text{Log } C = 3.870 + \underset{(0.153)}{0.178}\, X_2 + \underset{(0.139)}{0.363}\, X_3 + \underset{(0.172)}{0.276}\, X_4 + \underset{(0.333)}{1.258} \log H$$

$$+ \underset{(0.053)}{0.133} \log W - \underset{(0.052)}{0.086} \log L + \underset{(0.124)}{0.004} \log U + \underset{(0.034)}{0.026}\, T$$

$R = 0.72 \quad R^2 = 0.45$

$F(8,52) = 7.10$

An analysis of the residuals shows that errors are normal distributed and that no particular types are under- or overestimated by the regression equation.

The most important variables, which have coefficients significantly different from zero are height of the quay wall and width of the apron. The estimated coefficient for height indicates that costs per metre run of quay may vary more than proportional with height. A test on the difference between this coefficient and unity does not result in a significant difference. On the other hand, costs vary significantly less than proportional with width of apron.

An other interesting result is that the estimate shows that there might be returns to scale in constructing a greater length of quay. However, no significant difference from zero can be reported.

Tital range and superimposed quay loading seem to have little influence on costs.

This foregoing estimate shows clearly the cost differences between the construction types. Especially concrete walls have significantly higher costs than sheet pile walls. Taking the antilogarithms of the coefficients of the dummy variables leads to indices which indicate the proportion between cost of different constructions vs. cost of sheet pile walls with the same characteristics. These cost indices are:

sheet pile walls (= base)	1.-
open piled constructions	1.195
concrete walls	1.437
miscellaneous	1.318

As we learn from the estimates in this paragraph tidal range is of little relevance for costs. Tidal range, in particular, is heavily influencing the design of a quay wall (1), so that the dummy variables for type indication already include to some degree the influence of tidal variation.

Besides the indirect effect of tidal difference on costs through the design of the wall, it does have an immediate influence, for the height of a quay wall equals the sum of draft of the ship, tidal range and a safety margin. So the larger the tidal range the higher the quay to be built. Therefore it is sometimes more economical to built locks to exclude tidal variation from the quays (2).

In order to have an equation for practical purposes we estimated a regression which includes only the most important variables viz. height, apron, width, length, and dummy variables indicating the construction type. We obtained the following result (3).

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(1) E.g. An anchored sheet pile wall will be reinforced with only one tie when the quay wall is constructed within a non-tidal dock. Two ties are used when tidal range is considerable; one tie at high water level and the other at the low water level.

(2) In a future stage of our research on port analysis we will try to derive a decision rule for this problem, based on the cost functions of quay walls and locks, given a set of demand characteristics.

(3) For symbols see p. 5 and 7.

$$\log C = 3.673 + \underset{(0.300)}{1.353} \log H + \underset{(0.051)}{0.143} \log W - \underset{(0.051)}{0.091} \log H + \underset{(0.150)}{0.172} X_2$$

$$+ \underset{(0.135)}{0.352} X_3 + \underset{(0.164)}{0.245} X_4$$

n = 61
R = 0.72
F(6,54) = 9.59

This equation will be used in our further research on port planning.

3.2. Cost-equations for different construction types

In this paragraph cost equations for separete types of quays are derived. Because of the small sample sizes, only the most imported variables viz. height, apron width and length are involved in the regressions. In view of the small number of degrees of freedom in these equations one does not attach great importance to these results.

The cost-equations we estimated are the neperian logarithm of the following equation (1)

$$C_i = A.H_i^a W_i^b L_i^c E_i \qquad (2.I)$$

Anchored sheet pile walls and sheet pile walls with relieving platform are quay walls of similar construction. Therefore they are grouped in one category. However, we have carried out regressions for both groups and tested the hypothesis of equal regression coefficients.

These regressions result in (2)

- for anchored sheet pile walls

$$\log C = 2.621 + \underset{(0.719)}{1.555} \log H + \underset{(0.108)}{0.047} \log W + \underset{(0.172)}{0.033} \log L$$

n=12
R=0.68
F(3,8)=2.28
SSR=1.26

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(1) For symbols see p. 5 and 7

(2) See footnote 1 p. 6; SSR = sum of squared deviations from the regreggion.

- for sheet pile walls with relieving platform

$$\log C = 2.993 + \underset{(0.403)}{1.734} \log H + \underset{(0.056)}{0.231} \log W - \underset{(0.060)}{0.173} \log L \qquad n=23,\; R=0.80,\; F(3,19)=11.04,\; SSR=1.32$$

- for pooled data

$$\log C = 3.047 + \underset{(0.367)}{1.633} \log H + \underset{(0.052)}{0.128} \log W - \underset{(0.061)}{0.102} \log L \qquad n=35,\; R=0.67,\; F(3,31)=8.62,\; SSR=3.28$$

Chow's F-test (1) of equality between coefficients in two relations results in an F quantity of 1.82 which is lower than the F-value with (4,27) degrees of freedom at a one percent level so that the hypothesis of equality between the coefficients cannot be rejected.

Open piled constructions, concrete walls and miscellaneous types do not result in significant regressions at a five percent level as we can see from the following equations:

- open piled constructions

$$\log C = 2.052 + \underset{(0.603)}{1.095} \log H + \underset{(0.422)}{0.757} \log W + \underset{(0.166)}{0.020} \log L \qquad n=9,\; R=0.81,\; F(3,5)=3.27$$

-concrete walls

$$\log C = 6.761 + \underset{(0.941)}{0.296} \log H + \underset{(0.171)}{0.277} \log W - \underset{(0.150)}{0.129} \log L \qquad n=10,\; R=0.70,\; F(3,6)=1.94$$

- miscellaneous types

$$\log C = 5.482 + \underset{(0.312)}{0.751} \log H - \underset{(0.293)}{0.063} \log W - \underset{(0.266)}{0.003} \log H \qquad n=7,\; R=0.22,\; F(3,3)=0.05$$

These equations are given for the sake of completeness.

(1) See J. Johnston, Econometric Methods, p. 136-137.

4. CONCLUSIONS AND USE OF RESULTS

The conclusions that we can draw from this analysis is that there is a great variety in the design of quay walls. As Bertlin and Partners pointed out in their analysis (1) constructions especially designed to meet local conditions often turn out to be the most economical ones. A second conclusion on the constructions costs of quay walls is that there are increasing costs with height and in several cases decreasing costs with total length constructed. This is important, because tital variation increases the height of the quay wall and increases more than proportional costs. Taking this into account together with other cost increases of additional height due to tidal variations (such as dredging) it might be more economical to construct a lock.

It is practical to have the costs of quay wall constructions in a formal equation, especially for port planning. With these equations rough estimates of alternative quay wall structures can easily be obtained.

E.g. we want to predict the mean-cost of a quay wall with the following data

- type: concrete wall
- length: 5.000 m
- height: 16 m
- apron width: 5 m

We substitute these data into equation 4.I and obtain

$\log C = 7.227$

The point estimate of the mean cost therefore is

$C \approx 1365$ £/m

With these equations a "cost random generator" can be built so that uncertainty about costs of quay walls is more or less objectively known. In project appraisal under uncertainty (2) such informations is of great value.

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(1) See Bertlin and Partners, o.c., Vol. 1, p. 34.

(2) See e.g. Reutlinger, Shlomo, Techniques for Project Appraisal under uncertainty, BIRD, 1970.

Appendix i : Types of quay walls

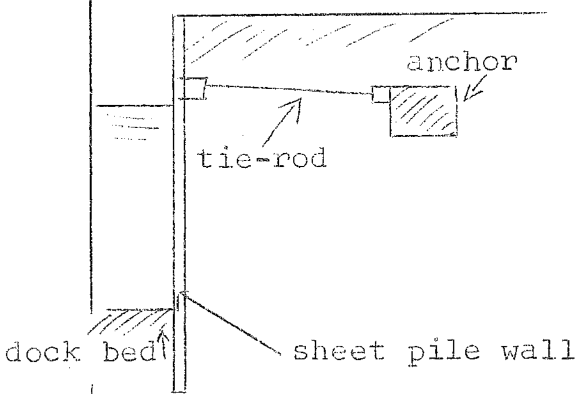

Fig. a. anchored sheet pile wall

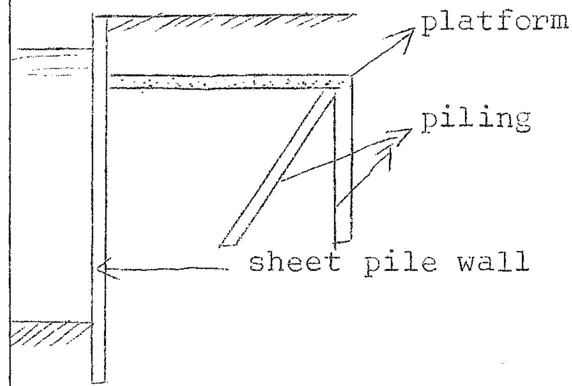

Fig. b. sheet pile wall with relieving platform

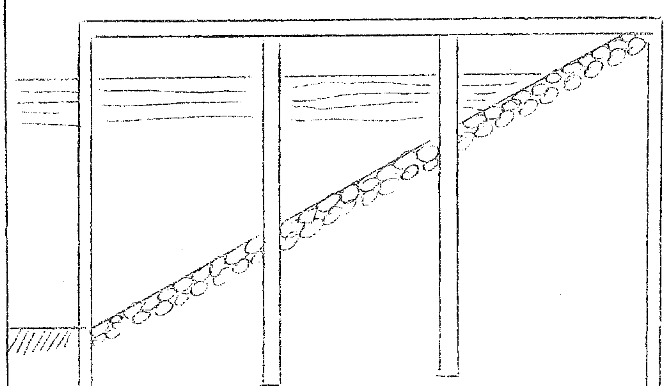

Fig. c. open piled construction

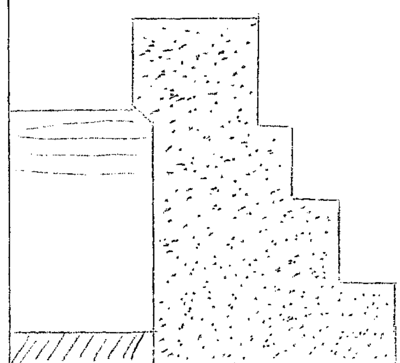

Fig. d. concrete wall

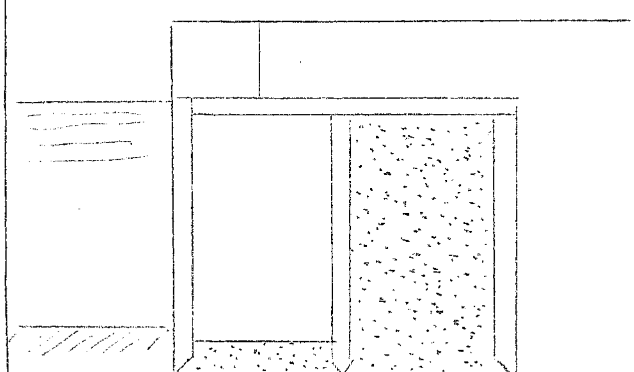

Fig. e. monolith

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