Analysis of gravity quay walls

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The Gravity quay wall is the most common type of walls used for harbor berths. The trend of ocean going deep draft vessels has made it difficult to satisfy equilibrium conditions for quite deep quay walls. Thus, factors affecting the stability of that type of berth should be looked at and investigated. This research focuses on the analysis of this type of retaining wall to illustrate the importance of each factor. A computer program (QWD) has been implemented (using visual basic.net and. Net framework technology) and developed for analysis of the gravity quay wall. Charts are offered to relate the effect of each factor on the final design.

تعتبر حوائط الارصفه التثاقليه هي الأكثر استخداما في أرصفة الموانئ وذلك لسهولة تنفيذها وطول عمرها الافتراضي، هناك عوامل كثيره تؤثر في اداء حوائط الارصفه. في هذا البحث تم التركيز على تحليل هذا النوع من الارصفه لتوضيح اهمية وتأثير كل عامل. بالاضافه الى ذلك تم تصميم وتنفيذ برنامج حاسب آلي بلغة الفيجوال بيسك للتحليل والتصميم مستخدما احدث تكنولوجيا في البرمجه اصدرتها مايكروسوفت في عام ٢٠٠٢ يقوم بتصميم وتحليل الارصفه التثاقليه والتحقق من اتزان الارصفه الموجودة. ومن خلال البحث تم عرض رسومات بيانيه توضح تأثير كل عامل على التصميم النهائي.

Keywords: Quay walls, Gravity walls, Harbors, Berths, Retaining walls

1. Introduction

Gravity quay walls are the most common types of docks. That is because of their durability; ease of construction and the possibility to reach a deep seabed level. The gravity quay wall has to be safe against the three design criteria, which are sliding, overturning and over stressing.

The design steps of gravity quay wall seem to be reasonably clear. However, the deep gravity walls are subjected to a great deal of external forces. In this case, the stability of the wall may be quite sensitive to many factors; depth of the wall, pulling force, soil characteristics; and base stratum characteristics. The effect of different factors on the stability needs to be investigated.

The study focuses on the analysis of gravity quay walls. Design steps are written in the form of computer program taking into account all factors affecting the analysis. This makes it possible to alternate factors in order to come to an ideal design.

2. Analysis of gravity quay walls

Two types of forces act on the gravity retaining quay wall, namely: stability forces and failure forces.

2.1. Stability forces

Two vertical stability forces are: weight of soil over the projection part of the blocks and own weight of blocks.

- *Weight of soil* = $\sum W1$; where:

W_1 = the weight of the soil resting on top of the projection part of the block (in tons), acting at its central of gravity (c.g.) of each part.

- *Weight of blocks* = $\sum W2$; where:

W_2= Own weight of block (in tons), acting at its center of gravity (c.g.).

- *Total stability forces acting on the wall:*

Total stability forces acting on the wall per meter length (in tons).

$\sum F_{stability}$ = = $\sum W_1$+ = $\sum W_2$+ vertical crane load (if exists).

2.2. Failure forces

There are four horizontal forces acting as static failure forces; Lateral earth pressures, the pull bollard, the live load effect (P_{LL}) and the horizontal crane load effect.

- *Pull bollard:*

Pull bollard (in tons), acting at 0.4 m above the top of quay wall level.

- Live load:
The horizontal force due to *L.L.* can be found from:

$$P_{LL} = \frac{1}{2} * L.L. * K_A * H^2 .$$

Acting at 0.5 *H*.
Where: *L.L.* is live load (in ton/m²), which depends on the type of the quay wall.
- Horizontal crane load:
If it is considered, Horizontal crane load (ton) ≅ 1/7 Vertical crane load.
Acting at the top of the wall.
- Static lateral earth pressures (dry layer):
Static lateral earth pressures dry layer is the area of backfill pressure of dry layer acting on the wall per meter (ton) calculating by coulomb.

$$P_{A(dry)} = \frac{1}{2} K_A \gamma d H_1^2 .$$

Acting at the centre of gravity (c.g.) of lateral earth pressures $\left(\frac{1}{3} H_1\right)$.
Where, γ_d the dry unit weight of soil (ton/m ³), and the active earth pressure coefficient is:

$$K_A = \frac{\cos^2(\phi - \theta)}{\cos^2\theta \cos(\delta + \theta)\left[1 + \sqrt{\frac{\sin(\delta + \phi)\sin(\phi - \beta)}{\cos(\delta + \theta)\cos(\beta - \theta)}}\right]^2} .$$

Where ,
θ is the inclination of wall (degree),
β is the slope angle of quay wall level (degree),
δ is the interface Friction angle of soil (degree), and
ϕ is the angle of internal friction of soil (degree).
- Static lateral earth pressures (submerged layer):
Lateral earth pressures submerged layer is the effect of the soil under the water level and can be calculated using the following equation:

$$P_{A(sub)} = \frac{1}{2} K_A \gamma sub H_2^2 .$$

Which acts at the centre of gravity (c.g.) of lateral earth pressures $\left(\frac{1}{3} H_2\right)$,

Where, γ_{sub} is the submerged unit weight of soil (ton/m³), and the active earth pressure coefficient:

$$K_A = \frac{\cos^2(\phi - \theta)}{\cos^2\theta \cos(\delta + \theta)\left[1 + \sqrt{\frac{\sin(\delta + \phi)\sin(\phi - \beta)}{\cos(\delta + \theta)\cos(\beta - \theta)}}\right]^2} .$$

Where
ϕ is the average angle of internal friction of soil and rock (degree), and

$\phi_{av} = \phi_r + 2/3\ (\phi_r - \phi_s)$.

Where,
ϕ_r is the angel of internal friction of rock, and
ϕ_s is the angel of internal friction of soil.
- Total static failure forces acting on the block:
Total failure forces (ton) is:

$\sum F_{failure}$ = ($P_{A\,(dry)}$ + $P_{A\,(sub)}$ + P_{LL} + Pull bollard + Horizontal crane load) * $\cos\delta$.

2.3. Safety against sliding

The factor of safety against sliding is expressed as:

$$F.O.S._{slding} = \frac{\sum F_{stability}}{\mu * \sum F_{failure}} \geq 1.5 ,$$

where μ = friction coefficient between blocks

3. Safety against overturning moment

The safety factor against overturning moment is expressed as:

$$F.O.S._{overturning} = \frac{\sum M_{stability}}{\sum M_{failure}} \geq 1.5 .$$

3.1. Stresses

$$e = \frac{blocklength}{2} - \left(\frac{\sum M_{stability} - \sum M_{failure}}{\sum F_{stability}}\right),$$

$$f_1 = \frac{-\sum F_{stability}}{blocklength}\left(1+\frac{6*e}{blocklength}\right) \text{ and}$$

$$f_2 = \frac{-\sum F_{stability}}{blocklength}\left(1-\frac{6*e}{blocklength}\right).$$

For last block the following conditions should be satisfied:
f_1 <= Bearing Capacity of the foundation soil, f_1, f_2 (–ve sign) compression and 2 * f_2 > f_1. *If* the conditions are not satisfied, we have to adjust the dimension of the bottom block and the one directly above the bottom block. If this is not enough, we may enlarge the third block from the base.

4. Analysis and parametric study

The computer program has been used extensively to analyze the plain concrete blocks gravity quay wall. Hundreds of runs have been done. Results have been studied, tabulated, and presented in the form of charts.

A gravity quay wall model has been analyzed. Parameters implemented are shown in table 1. Fig. 1 shows configuration of the plain concrete gravity quay wall.

Fig. 2 shows the relationship between lateral pressure force acting on the bottom block and he angle of internal friction for static cases, respectively.

It is clear that the angle of internal friction has a significant influence on the magnitude of pressure acting on the wall. A coarse material backfill should be instructed behind the wall with width equal at least 0.5 of the wall height at H.W.L level with slope 1:1 all the way down. Deep walls are subjected to increasing lateral pressures. Thus, increasing the width of the coarse backfill material to be similar to the wall height may be recommended. This probably decreases the lateral pressures by a percentage of 25%. The improper construct of the backfill or failing to do so, for any reason, may double the horizontal forces.

Table 1
parameters of the quay wall model

Parameter	Chosen value
Draft (m)	12
Clearance (m)	1
Tidal range (m)	1.5
Distance between upper surface of head and H.W.L (m)	1.5
Lower surface level of the head (m)	+0.75
Height of each block (m)	2.25
Height of first block (m)	2.5
Saturated unit weight of concrete (ton/m^3)	2.2
Buoyant unit weight of concrete (ton/m^3)	1.2
Friction coefficient (concrete/ concrete)	0.4
Friction coefficient (concrete/ rock)	0.5
Angle of internal friction of soil (degree)	30
Angle of internal friction of back fill (degree)	45
Average dry unit weight of soil (ton/m^3)	1.85
Average buoyant unit weight of soil (ton/m^3)	0.9
Bearing capacity of soil (ton/m^2)	25
Buoyant unit weight of rock (ton/m^2)	1
Angle of interface friction (soil/structure) (degree)	0
Pulling force on bollard (ton/m)	2
Live load (ton/m2)	2

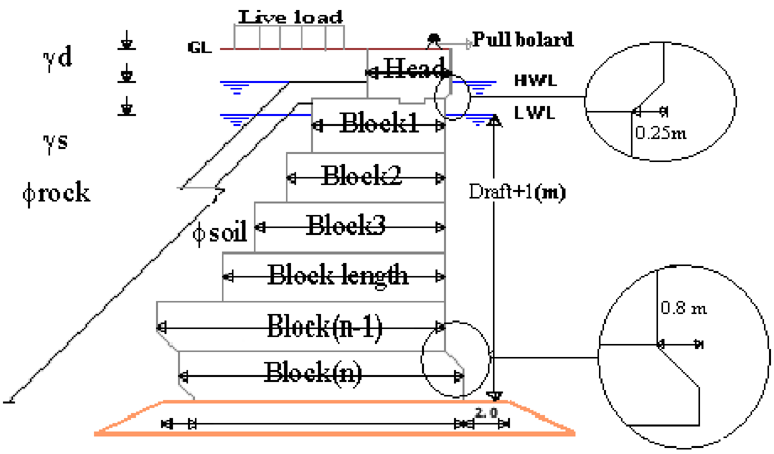

Fig. 1. Configuration of the plain concrete gravity quay wall.

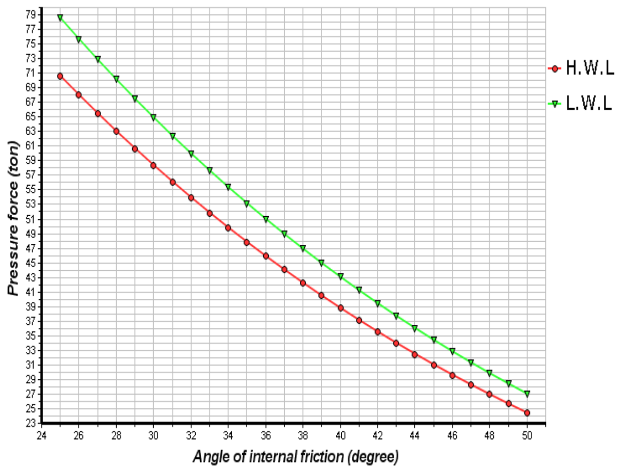

Fig. 2. Relationship between lateral pressure force acting on the bottom block and the angle of internal friction.

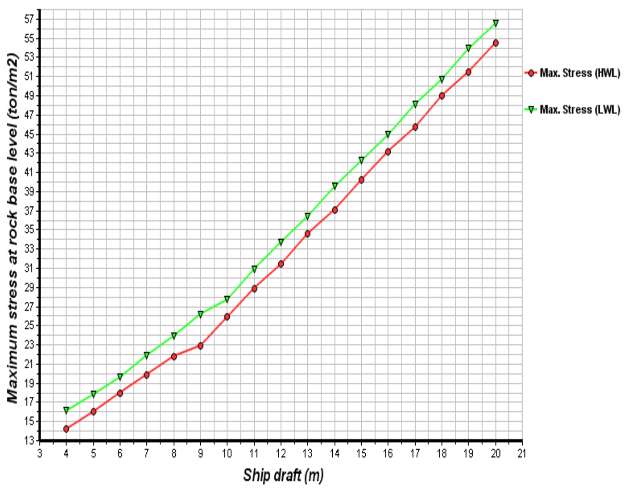

Fig. 3. Effect of ship draft on the maximum stress at base rock level.

Ship draft is an quite essential factor because lateral pressures and instability moments dramatically increase with depth. Fig. 3 shows the tremendous increase in maximum stress at rock base level with the increase of depth. Moreover, the difference between stresses at front and the rear of the bottom block increases. In deep walls, improvement of soil condition may be necessary. Decreasing pressures by increasing the angle of internal friction may help. Using an anchor to take some of the horizontal loads may be a solution, particularly in seismic cases. Geotextile may also be used.

Gun pulling force is usually taken (2 t/m) when the total pulling force is increased; the number of mooring guns is increased too.

Fig. 4 shows the relationship between the maximum stress and the magnitude of live load.

Live loads are usually taken to increase lateral force acting horizontally, it is assumed to act at the area behind the wall. Live load increases the maximum stress as well as the difference between maximum and minimum stresses.

Unit weight of the concrete block ranges usually from 2.0 to 2.4 (t/m^3). Fig. 5 shows that going for higher unit weight minimize the difference between the maximum and minimum stresses at the rock base level.

Eccentricity of the resultant of external forces depends on normal forces and external moments acting on the rock base surface. Thus, if stresses are not favorable, reshaping the bottom block can move center of gravity of

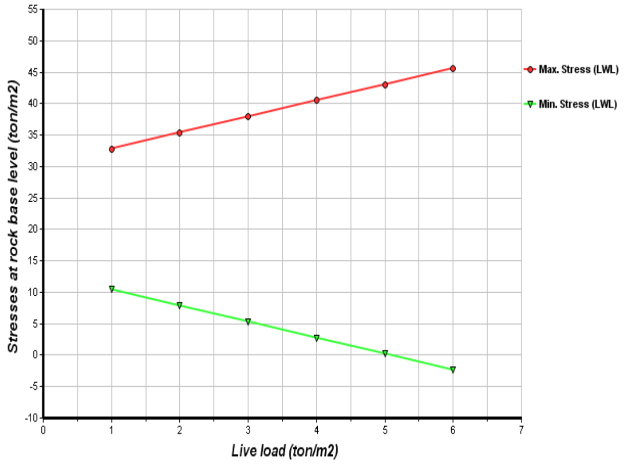

Fig. 4. Relationship between live load and maximum stress at base rock level.

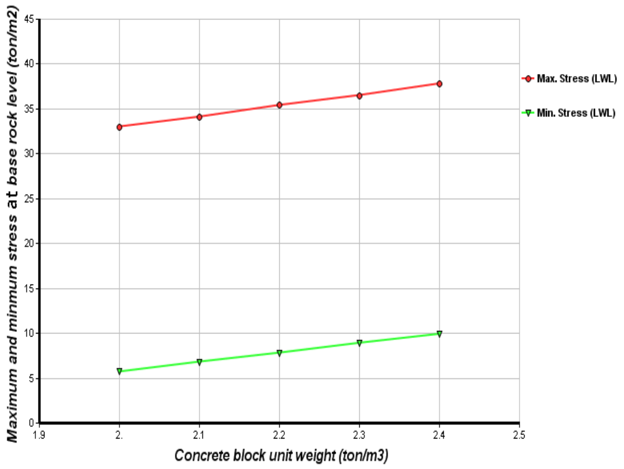

Fig. 5. Effect of concrete unit weight on stresses at rock base level.

the contact area. Also, increasing the length of the second block from the bottom may have a favorable effect. Fig. 6 shows the effect of the length of the second block from the bottom on stresses at rock base level. Increasing that length has two positive effects; decreasing the maximum stress and alleviating the unfavorable difference between maximum and minimum stresses.

Bearing stratum strength is an essential factor on the stability and workability of quay walls. Quay wall with small and moderate depth can be constructed on soil with moderate strength. Deep quay wall needs either originally strong soil or soil improvement or replacement. Effect of bearing stratum strength on the configuration of blocks (in terms of quay wall weight), is shown in fig. 7.

It can be seen that limiting the bearing capacity may result in dramatic increase of the last two or three blocks. In other words, to satisfy the bearing capacity condition by decreasing the maximum stresses, the blocks should be increased in length and total weight and stability moments are increased.

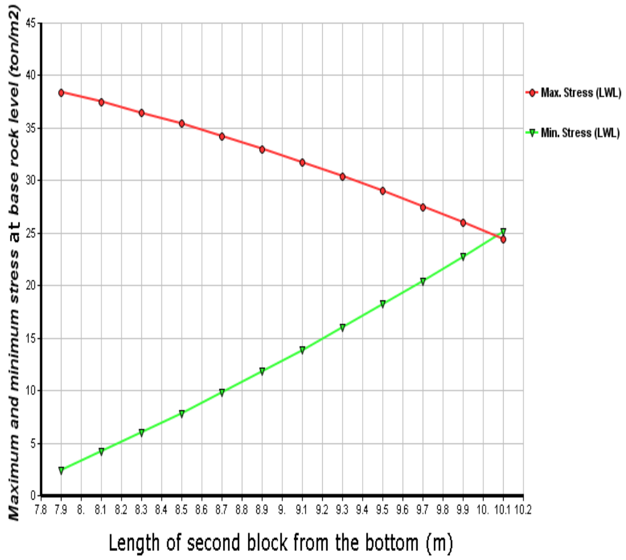

Fig. 6. Effect of length of the second block from the bottom on stresses at rock base level.

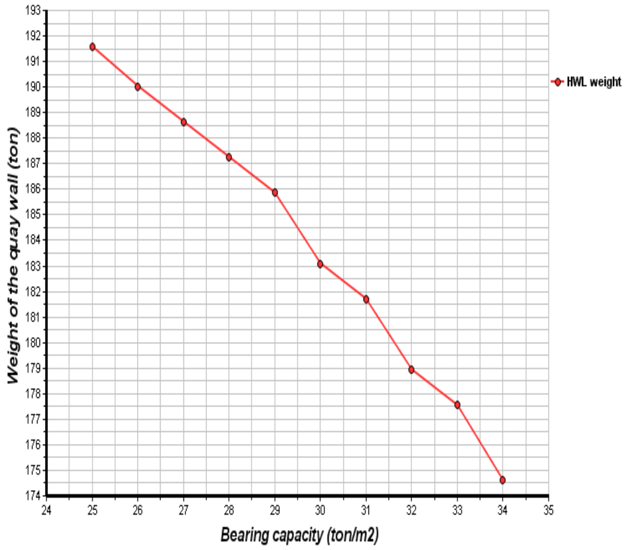

Fig. 7. Effect of bearing capacity of soil on weight of quay wall.

5. Conclusions and recommendations

Design of plain concrete blocks gravity quay wall is usually a clear-cut one. However, for deep docks or those subjected to huge forces and resting on semi-strong soil, stability is difficult to achieve. Factors affecting equilibrium condition become essential and their influence on the final design of the gravity quay wall needs to be investigated.

In this research, a computer program has been developed and implemented for direct analysis of gravity quay wall. Optimum configuration of concrete block can be achieved by altering some of or all the factors.

A set of charts has been produced to illustrate the criteria of the plain concrete quay wall and the relationship between the output and the affecting factors.

From the analysis and the parametric study the following may be concluded and recommended:

1. The back fill characteristics have a great influence on the stability of gravity quay wall.
2. A ship load and dimensions affect the berth in terms of pollard force, magnitude of live load, and depth of the quay wall.
3. The concrete crown should be carefully checked, since it is the most critical part of the quay wall particularly when the pulling force acting on mooring guns is quite large. Thus, a groove of (1m) length should be done to prevent sliding and create a shear resistance.
4. Dimensions of each block can be determined by checking sliding first then checking for overturning and stresses.
5. If stresses on the rock base are not appropriate, the center of the last block can be moved toward the sea by reshaping the block. If this step is not enough, the second block from bottom can be enlarged and checked against shear failure. If more steps are needed we may increase the length of third block from the bottom to be (1m) longer than the length of second block from the bottom.
6. Configuration of the quay wall can be improved by reducing lateral forces, which can be achieved by extending the backfill to a distance equal to the height of the wall.
7. In deep docks (more than 12m) founded on relatively weak soil (strength less than $15t/m^2$), a replacement or strengthen of bearing soil is quite needed.
8. Live load should be applied on the berth just behind the blocks. It means that, it produces lateral pressure and may not contribute to weights.
9. Increasing the unit weight of the concrete participates into the stability of the wall. Therefore, it is recommended to use blocks with unit weight not less than $2.4t/m^3$ particularly for deep quay walls.
10. It is recommended to choose the case of L.W.L in the design, because it produces the worst case concerning stresses at rock base level.
11. If stresses developing on the bearing stratum are not acceptable, anchors may be constructed or soil behind the wall may be reinforced by geotexile.

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