Thesis,
on the
Sea Walls
of
South Boston Flats,
by
Martin Gay.

The walls recently built on the flats off South Boston whose location is shown in Plate I of the accompanying drawings, were originally intended as a Harbor improvement merely.

The ebb tide from Fort Point Channel met the flood tide in the Harbor and was neutralized and in the area where the tides met a gradual deposit took place and formed the dangerous shallows known as "Anchorage Shoals".

By confining the current to a narrower channel and preventing its diffusing itself over the large area of flats it was thought that the ebb tide would have a preponderance over the flood and would no longer deposit

its sediment in the Harbor.
Since the walls were built this has proved to be the case and there is now no tendancy to shoaling in this locality.
So far at least as the first object of this project is concerned it has been a success.
The second object was to make land for commercial purposes, and in order that all this territory which it was proposed to create might be available for commerce it was necessary to make it accessible from the deep water beyond. Therefore a channel has been dredged along the length of the wall and out to the deep water of the main ship channel, as shown by the dotted line

in Plate I. This dredging gives for the most part a depth of 23 feet at mean low water of Spring tides, which is the datum to which all measurements are referred. It is proposed eventually to enclose and fill in about 700 or 800 acres of flats lying between Fort Point Channel and Castle Island in one direction and the North East shore of South Boston and the main channel of Boston Harbor in the other.

With the exception of a small portion owned by the Boston Wharf Co., the New York and New England R.R. Co., and the Boston and Albany R.R. Co. these flats are owned and will be enclosed and filled by the Commonwealth through the agency of the Harbor Commission. The material for filling is dredged from the Harbor and spread upon the flats, and in this way the project has been a great advantage to the commerce of Boston for the dredging has added a safe anchorage ground in the Upper Harbor of about 500 acres.

The walls are built up to grade 16 or 16 feet above mean low water, and the flats behind them are filled up to grade 13 with the material dredged from the channel, and the remaining 3 feet to the top of the wall with clean sand brought from the country.

When the filling first began scow loads of the mud sand and clay from the bottom were floated on to the flats at high water and dumped, but when the filling was raised to high for this the scows were towed to the side of the wall and their contents discharged. It was then dredged up by another dredge stationed at that point and lifted over the wall into dump cars which ran out over the flats on tramways and deposited the filling. By being worked over in this way the originally tolerably stiff sand and clay became almost liquid and spread itself out over the flats at a slope frequently as flat as 1 vertical to 18 horizontal.

This when first put in makes

of course a very trying filling for retaining walls, but as the water drains off and it becomes dry it gradually gets quite hard and firm.

The cost of filling is 39 cents per superficial foot of area filled.

Up to the present time there have been three different forms of wall built; the first a light sea-wall along Fort Point Channel the location of which is shown in Plate I; a heavy sea wall beginning where the light wall ends and extending to the first dock; and another heavier wall between the first and second docks. This last is now in process of construction.

I propose to discuss each

of these walls in turn and see if they appear to be in danger of giving way through the weakness of the wall itself or through the weakness of the foundation on which it rests. The whole work has been in the charge of Mr. Edw. S. Philbrick, and has been executed by Messrs. Clapp and Ballou contractors.

The light sea wall was begun in November 1873. It begins on Fort-Point Channel at the boundary line of the Boston Wharf Co. and runs 641 feet to the beginning of the heavy wall. There are also about 1800 feet of this form of wall around the dock shown in Plates I and II. A section of the wall is shown in Plate II, representing the backing and the platform which it is proposed to build along the whole extent of the walls to act as wharves and to bridge over the space between the walls and the deep water of the ships berths.

The foundation is on piles driven five in a row and spaced 2½ feet from centre to centre of each row. The piles were driven down into a hard stratum of clay and their heads sawed off even with each other 2½ feet below low water.

For ~~two~~ 2 feet below the heads of the piles the material had been removed and this space was filled with stone-chip ballast or oyster shells and well rammed.

On the heads of the piles were spiked two layers of spruce planking

12" × 3" at right angles to each other. On top of this planking the wall is built of granite rubble-wall stone with headers enough to pin it together.

It is 9 feet broad at base, 6 feet at top and 18 feet high, with a batter on the front of 1 horizontal to 6 vertical, and on the back 1 horizontal to 18 vertical.

It is backed by oyster shells, rip-rap or sand, and as the latter is the most trying material of the three I have assumed it to be used in the following calculations.

To find if the wall is in danger of failing by rotating I have followed the general plan of Prof. Rankine's investigation of retaining walls; and consider the natural slope of the filling the same as the natural slope of the backing. See Rankine's C. E. page 410. The most severe stress will come upon the wall when there is filling behind to the top, and low water of spring tides in front.

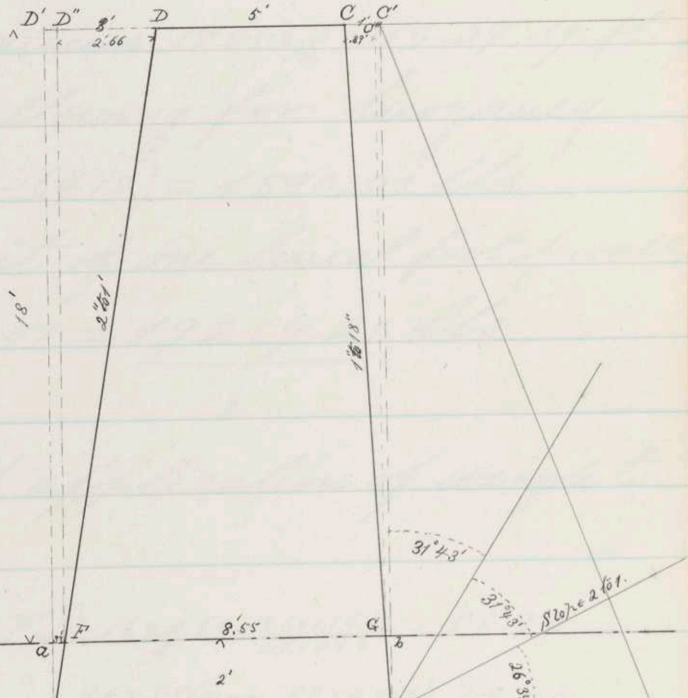
Wt. cu. ft. of gravel (damp) = 134 lbs

" " " " " saturated = 142 "

" " " " salt water = 64.18 "

" " " " masonry = 163 "

Slope of gravel = 2 to 1 = 26°34'



The horizontal thrust of the earth is equal to the weight of the prism BC'X.

Length of BX = $18 \times \frac{1-\sin 26°34'}{1+\sin 26°34'}$ = 6.875 ft.
Area of BCX = $\frac{18 \times 6.875}{2}$ = 61.874 sq. ft.
Weight of prism BCX = 61.874 × 134 = 8291.116 lbs.

Area CDFG = $\frac{5+8.55}{2} \times 16$ = 108.4 sq. ft.
Weight " = 108.4 × 163 = 17669.2 lbs.
Area ABGF = $\frac{9+8.55}{2} \times 2$ = 17.55 sq. ft.
Deduct $\frac{1}{12}$ for vacancies $17.55 \times \frac{11}{12}$ = 16.09 sq. ft.
Weight of ABGF allowing for buoyancy of water = 16.09(163 − 64.18) = 1590.01 lbs.
Resultant weight of one lineal foot of wall
= 17669.2 + 1590.01 = 19259.21 lbs.

To find point of application of weight of wall.

Moment of FDD" about FD = $\frac{16 \times 2.66}{2} \times \frac{2.66 \times 16 \times 2}{2 \times 16 \times 3}$ = 18.86
" "GCC" " " = $\frac{16 \times .89}{2}\left(8.55 - \frac{.89 \times 2 \times 16}{2 \times 16 \times 3}\right)$ = 58.50

77.36

" "FGC"D " " = $8.55 \times 16 \times \frac{8.55}{2}$ = 584.82

" "FGCD " " = 507.46

Distance of centre of gravity FGCD from FD = moment divided by area =

$507.46 \div \frac{8.55+5}{2} \times 16 = 4.68$ ft.

Distance of c.g. from ~~F~~AD' $= 4.68 + .33 = 5.01$ ft.

Moment of aFA about AD' $= \frac{.333 \times 2}{2} \times \frac{.333 \times 2 \times 2}{2 \times 2 \times 3} = 0.36$

" " bBG " " $= \frac{.11 \times 2}{2}\left(9 - \frac{.11 \times 2 \times 2}{2 \times 2 \times 3}\right) = 0.99$

1.35

" " ABba " " $= 9 \times 2 \times \frac{9}{2} = 81.$

1.35

" " ABGF' " " $= 79.65$

Area " " $= \frac{9 + 8.55}{2} \times 2 = 17.55$

Dist of c.g. of " from AD' $= 79.65 \div 17.55 = 4.53$ ft.

Distance of c.g. of wall from AD' =

$(17669.2 \times 5.01 + 1590.01 \times 4.53) \div (17669.2 + 1590.01)$

$= 4.97$ ft.

Distance of point of application of weight of wall from centre of base =

$4.97 - 4.5 = 0.47$ ft.

The wall will not rotate about its

extreme edge or toe but about a point called the "centre of resistance" which in the best examples of masonry is $\frac{3}{8}$ of the thickness of the base from the centre. Calling t the thickness of the base and equating the moment of stability of the wall with the moment of the earth pressure,

$(\frac{3}{8}+\frac{.47}{9})t \times 19259.21 = 6 \times 8291.116$ hence

$t = \underline{6.05}$ ft. which is 2.95 ft. less than the given thickness and shows that the wall at the base has a factor of safety of about $1\frac{1}{2}$.

There is evidently no danger of the wall overturning from its base but it may do so at some other joint of the masonry courses, and it will be well to calculate the necessary thickness of the wall at some point say

half way up.
Weight of prism of earth $= 9\frac{1-\sin 26°34'}{1+\sin 26°34'} \times \frac{9}{2} \times 134 = 2072.779$ lbs
= earth thrust.
Weight of masonry $= \frac{7+5}{2} 9 \times 163 = 8802.$ lbs.

$7 \times 9 \times 3.5 - \frac{9 \times 1.5}{2} \times .5 - \frac{.5 \times 9 \times 5.33}{2} = 205.132 =$
moment of upper part of wall about its outer edge.
$\frac{7+5}{2} \times 9 = 54 =$ area of upper part of wall, hence
$205.132 \div 54 = 3.8$ ft. = distance of point of application of weight of wall from edge.
Distance from centre $= 3.8 - 3.5 = 0.3$ ft.
Equating moment of stability with moment of earth pressure;
$(\frac{3}{8} + \frac{.3}{7}) t \times 8802 = 2072.779 \times 3$ hence
$t = 1.69$ ft. Which shows that the thickness (7 ft.) of the wall 9 ft from the base has a factor of safety of over 4, and it is evident that if the wall gives way by overturning it will be from the base, which

was found above to be amply thick to resist this tendancy.

There is a certain friction between the filling and the back of the wall which many authorities upon this subject do not take into consideration at all, and which if it could be entirely relied upon would exert a powerful influence upon the stability of the structure.

By a series of experiments made at the office of the Engineer in charge of the work it was found that the friction of granite on moist gravel was 38 per cent of its weight. The force which causes friction in this case is the horizontal thrust of the earth equal to 8291.116 lbs, ~~therefore~~ the friction

on the back of the wall equals
$8291.116 \times .38 = 3150.62$ lbs.
The perpendicular distance of the line of action of this force from the centre of resistance is sufficiently near $(\frac{1}{2} + \frac{3}{8})t$ for practical purposes. Then adding the moment of this force to the equation found before on page 13 gives $\left[\left(\frac{3}{8} + \frac{.47}{9}\right) \times 19259.21 + \left(\frac{1}{2} + \frac{3}{8}\right) \times 3150.624\right] t = 6 \times 8291.116$ hence $t = 4.528$ ft which gives a factor of safety of nearly 2.

But this friction cannot always be depended upon, it varies with the moisture or dryness of the materials, and any sudden shock or jar may destroy it. It is erring on the side of safety at any rate to disregard it.

It has been demonstrated by M. Poncelet in a memoir published in the "Mémorial de l'Officier du Génie" that if a wall is strong enough to resist the tendency of the earth pressure to overturn it, it is in no danger of giving way by sliding at the foundation or one course upon another.

It is easy to show that this wall will not slide for the angle of repose of the backing is 26°34' or a slope of 2 to 1 whereas the angle which the resultant pressure makes with the vertical to the base is as 2.32 to 1.

As there was no record kept of the pile-driving of this wall beyond the number of piles and the depth to which they were driven, there is no data to be had with which the load each pile will bear can be computed with accuracy. But Prof. Rankine states that a pile driven till it reaches firm ground will support 1000 lbs. per square inch of head.

These piles are driven on an average about 20 feet below low water, and an average of 8 feet into a stratum of hard clay, and it can be seen as follows if the pressure per square inch on the piles exceeds the limit stated above.

The pressure on the base of the wall due to the earth thrust is the vertical component of the stress of which 8291.116 lbs.

is the horizontal component.

Pressure per lineal foot of base = weight of wall + vertical component of earth pressure $= 19259.21 + \frac{8291.116}{\tan 31^\circ 43'} =$ 32675.032 lbs.

The piles are spaced $2\frac{1}{2}$ feet from row to row with 5 piles in each row, therefore each pile has to carry $32675.032 \times \frac{2.5}{5} = 16337.516$ lbs.

The area of each pile head is about 78.5 square inches, so that $16337.516 \div 78.5$ gives a pressure on each pile of about 208 lbs. per square inch of head.

This is on the supposition that the load is uniformly distributed which is not quite true.

The most unfavorable circumstances under which the wall would stand would give a pressure on the outer pile of double the uniform pressure used above, but even this would be well within the limit of 1000 lbs. per square inch, and it seems safe to assume that the wall will not sink to a dangerous extent.

The cost of this wall was $39. per lineal foot.

The heavy sea wall which runs from the end of the light-wall round the curve to the first dock was began in October 1873. It is 765 feet long and cost $236 per lineal foot.
Its location is shown in Plate I and a section of it in Plate II marked

"section through A–B".

A trench was excavated on the line marked out for this wall, 45 feet wide and 23 feet below low water or down to the hard clay if it was not reached at that depth. This trench was filled with broken quarry stone, each piece weighing not less than 75 lbs. The stones were deposited in layers and each layer carefully worked over and levelled off by a diver with a crow-bar.

The filling is 45 feet wide at the bottom and for 3 feet up, from whence it slopes to 18 feet wide at a depth of 11 feet below mean low water. The filling is levelled off at the top with smaller chips of quarry stone to receive the wall, and the interstices of the outer slope are filled likewise.

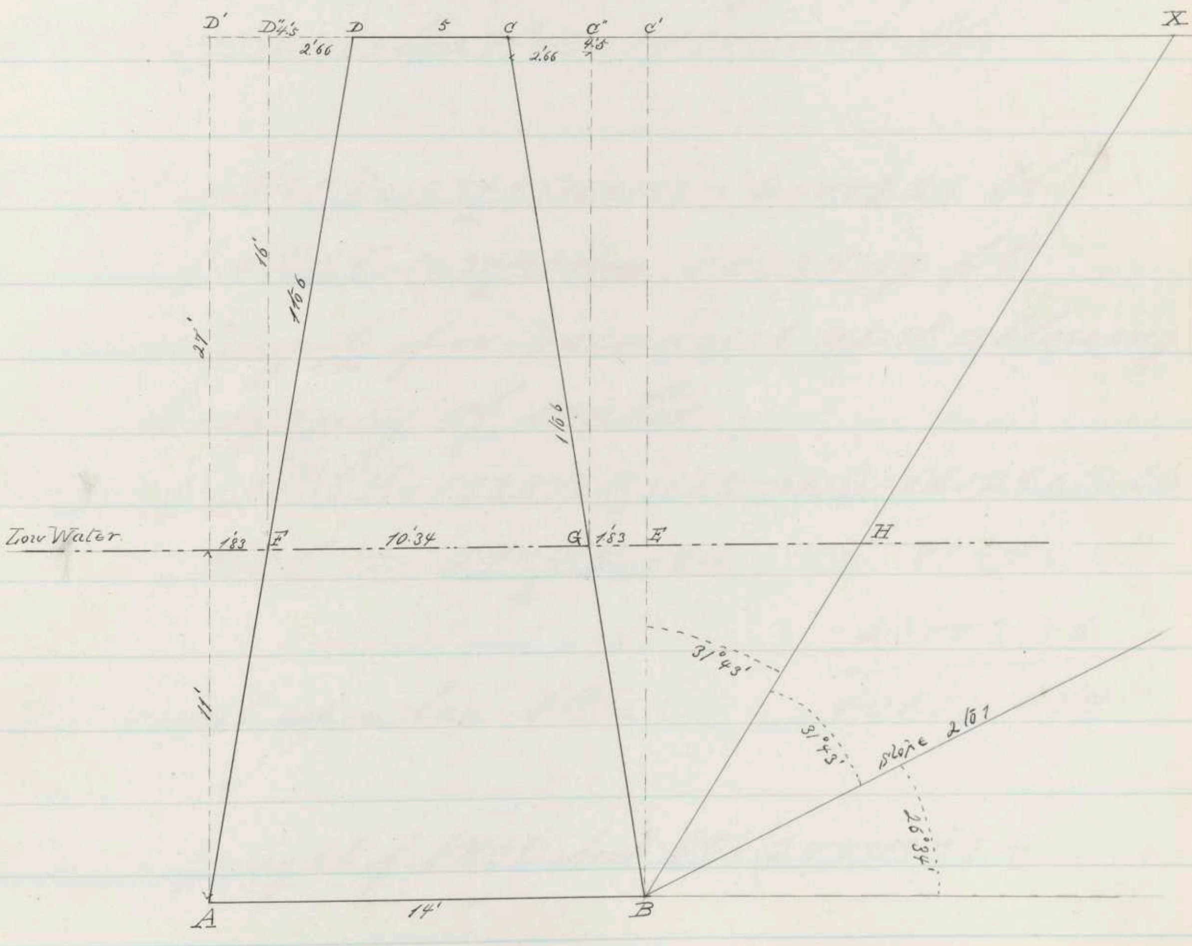
From the base to the height of 1 foot below low water the wall is built of granite dimension stone, laid by divers, in courses of 2 feet rise each. The courses are alternately headers and stretchers.

From 1 foot below low water to the top of the wall each course is of headers and stretchers laid in cement.

The wall is ballasted like the other with gravel, rip-rap, or oyster shells.

In order to distinguish between the saturated sand of the filling which is under water and the damp sand above, it is necessary in this case to calculate the weight of the actual prism of earth which tends to slide off.

In the former case BC'X represented the thrust against the wall, in this case BC'X is the prism of earth whose horizontal component is the thrust against the wall.



Length of C'X = 27 tan 31°43' = 16.686 ft.
" " EH = 11 tan 31°43' = 6.798 ft.
Area of E'HXC' = $\frac{16.686 + 6.798}{2}$ 16 = 187.872 sq. ft.
" " BHE' = $\frac{11 \times 6.798}{2}$ = 37.389 " "
Weight of E'HXC' = 187.872 × 134 = 25174.848 lbs.
" " BHE' = 37.389 (~~142~~ − 64.18) = 2909.612 "
" " BXC' = 28084.460 "
Horizontal component of weight of
BXC' = 28084.46 × tan 31°43' = 17356.477 lbs.

Weight of FACD = $\frac{10.34 + 5}{2}$ 16 × 163 = 20003.36 lbs.
Area of ABGF = $\frac{10.34 + 14}{2}$ 11 = 133.87 sq. ft.
Deducting $\frac{1}{12}$ for vacancies and allowing for buoyancy of water.
Weight of ABGF = 133.87 × $\frac{11}{12}$ (163 − 64.18) = 12126.614 lbs
" " BCC' = $\frac{27 \times 4.5}{2}$ × 134 = 8140.5 "
20003.36 "
Total weight upon base AB = 40270.474 "

Moment of weight of ABCD about AD' = (20003.36 +

12126.614) 7 = - - - 224909.818

Moment of weight of BCC' about AD' =

$8140.5\left(14 - \frac{2.25 \times 18}{27}\right) =$ 101756.25

326666.068

Distance of point of application of resultant weight from AD' = 326666.068 ÷ 40270.474 = 8.11 ft. Distance of point of application from center of base = 9 − 8.11 = 1.11 ft.

Pressure of water

$= 64.18 \times \frac{11 \times 11}{2} = 3882.89$ lbs (nearly)

Equating the moment of the earth pressure with the moment of the water pressure and the moment of stability, gives,

$\left(\frac{3}{8} + \frac{1.11}{14}\right) t \times 40270.474 = 9 \times 17356.477 - \frac{11}{3} \times 3882.89$

hence $t = 7.78$ ft., which gives without considering the friction of the gravel on the back of the wall a factor of safety of about 1.8

Taking another section at the height of mean low water;

Weight of prism of earth $= 16 \tan 31°43' \times \frac{16}{2} \times 134 = 10600.07$ lbs.

Earth thrust or horizontal component of weight of prism =

$10600.07 \times \tan 31°43' = \underline{6550.95}$ lbs.

Weight of masonry $= \frac{5 + 10.34}{2} \times 16 \times 163 = 20003.36$ lbs

" " $GCC' = \frac{16 \times 2.66}{2} \times 134 = 2851.52$ "

Total weight on base FG $= \underline{22854.88}$ "

Distance of point of application of resultant weight from edge of wall $= 20003.36 \times 10.34 + 2851.52 \left(10.34 - \frac{2.66 \times 2 \times 16}{2 \times 16 \times 3}\right) \div 22854.88 = 5.7$ ft.

Distance from centre of base =

$5.7 - 5.17 = 0.53$ ft.

Equating moment of earth pressure with moment of stability gives

$\left(\frac{3}{8} + \frac{.53}{10.34}\right) t \times 22854.88 = 6550.95 \times \frac{16}{3}$ hence

$t = 3.5$, which shows that

at 11 ft from the base the wall has a factor of safety of nearly 3.

It is not necessary to discuss the probability of this wall sinking because it has a broader base and is not so heavy as the next one to be calculated, and therefore if the foundation of that one is found to be safe it is quite certain that this wall will be safe also.

The location of the heavy wall between the docks is shown in Plate I but there is no section of it in the drawings. It is 39 feet high 18 feet broad at base and 5 feet broad at top, with a straight back and a batter of 1 to 3 in front. The base rests upon a foundation of broken stone laid in a trench 36 ft. wide and 3 feet deep. Like the other heavy wall it is built of granite laid without cement below low water, laid with cement above.

The ballast is to be of gravel, oyster-shells, or rip-rap.

The wall will cost $248.50 per lineal ft.

It is in process of construction now and at the present time is built up to within a few feet of mean low water.

Length of CX = 39 tan 31°43′ = 24.102 ft.

" " GH = 23 tan 31°43′ = 14.214 "

Area of GHXC = $\frac{24.102+14.214}{2}$.16 = 306.528 sq. ft.

Area of BHG = $\frac{23 \times 14.214}{2}$ = 163.461 sq. ft.
Weight of GHXC = 306.528 × 134 = 41074.752 lbs.
" " BHG = 163.461 (142 − 64.18) = 12720.535 "
Total weight of prism BCX = 53795.287 "
Horizontal thrust on wall =
53796.287 tan 31°43′ = 83246.025 lbs.

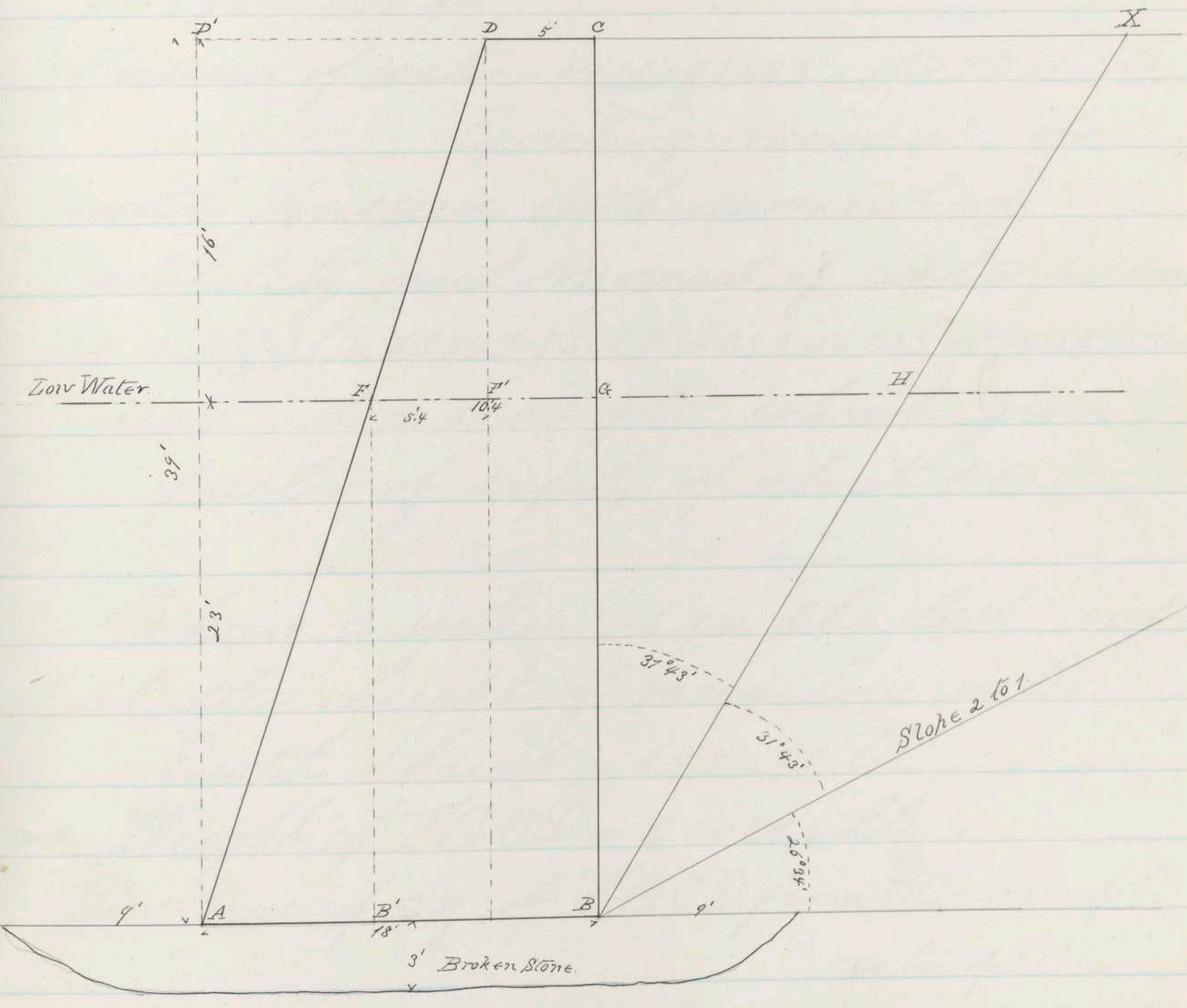
Weight of FGCD = $\frac{5+10.4}{2} \times 16 \times 163$ = 20081.6 lbs.
Area of ABGF′ = $\frac{18+10.4}{2} \times 23$ = 328.6 sq. ft.
Allowing for buoyancy of water and $\frac{1}{12}$ for vacancies, weight of
ABGF′ = $328.6 \times \frac{11}{12}(163 - 64.18)$ = 29766.231 lbs.
20081.6 "
Weight of 1 lineal foot of wall = 49847.831 "

Moment of FGCD about BC = 16 × 5 × 2.5 = 200.
" " FF′D " " = $\frac{16 \times 5.4}{2}\left(\frac{2 \times 16 \times 2.7}{3 \times 16} + 5\right)$ = 293.76
" " FGCD " " = 493.76
Distance of c.g. FGCD from BC =
$1193.6 \div (5+10.4)\frac{16}{2}$ = 4.01 ft.

Moment of B'BGF about BC = 23×10.4×5.2 = 1243.84

" " ABF " " $= \frac{23 \times 7.6}{2}\left(10.4 + \frac{2 \times 23 \times 3.5}{3 \times 23}\right) = 1180.37$

" " ABGF " " = 2374.21



Distance of c.g. of ABGF from BC =
$2374.21 \div (18+10.4)\frac{23}{2} = 7.27$ ft.
Distance of c.g. of wall from BC =
$(20081.6 \times 4.01 + 29766.231 \times 7.27) \div 49847.831 = 5.96$ ft.
Distance of c.g. from centre of wall =
$9 - 5.96 = 3.04$ ft.
Pressure of water $= \frac{64.18 \times 23 \times 23}{2} = 16975.61$ lbs
Equating moment of earth pressure with moment of stability and moment of water pressure
$\left(\frac{3}{8} + \frac{3.04}{18}\right) t \times 49847.831 = 13 \times 33246.025 - \frac{23}{3} \times 16975.61$
hence $t = 11.14$ ft. which gives a factor of safety of about 1.6.

Taking a section as in the last wall at the height of mean low water.
Earth thrust = 6550.95 lbs.
Weight of FGCD = 20081.6 lbs
Distance of c.g. of FGCD from BC = 4.01 ft.
" " " " " " centre of FG =
$5.2 - 4.01 = 1.19$ ft.

Equating moment of earth pressure with moment of stability, gives

$\left(\frac{3}{8} + \frac{1.19}{10.4}\right) t^2 \times 20081.6 = 6550.95 \times \frac{16}{3}$ hence

$t = 3.56$ ft. which gives the wall at this section a factor of safety of nearly 3.

During the early part of this work Mr. Jos. P. Frizell made a series of experiments upon the bottom on which these walls are built; by weighting a pile and noticing the depth to which it sank in a given time; and also by measuring the penetration of a pile under the blows of a pile-driver. The following penetration of a pile under blows from a hammer which weighed 1385 lbs. is a fair example of the results of all these experiments.

1st blow, fall 7 ft. 7½ in., penetration 8⅞ in.
2nd " , " 8 " 4⅗ ", " 11⅛ "
3rd " , " 9 " 3½ ", " 11¾ "

By an approximate method Mr. Frizell finds the relation between a blow on a pile and the steady load required to produce the same effect.

Let W = weight of ram, in pounds.
" h = height through which it falls in feet.
" d = penetration of pile in feet
" P = pressure upon head of pile while sinking, in pounds.

The work accumulated in the hammer during its fall is Wh.
The work expended upon the pile while sinking is Pd.
These being assumed equal gives $P = \frac{h}{d} W$. This is not true but is sufficiently correct for the present

purpose. Applying it to the data given above gives;

1st Elbow. $P = \frac{7.62}{.74} \times 1385 = 14265$ lbs $= 62247$ lbs per sq. ft.

2nd " , $P = \frac{8.364}{.927} \times 1385 = 12496$ " $= 54530$ " " " "

3rd " , $P = \frac{9.29}{.98} \times 1385 = 13129$ " $= 57291$ " " " "

Pressure per square foot of base $= (49847.831 + \frac{33246.025}{\tan 31°43'}) \div 18 = 5758$ lbs, supposing the pressure to be uniformly distributed. This is not the case, as the maximum pressure is at the outside or toe of the wall and the greatest thrust which the wall could resist would give a pressure of zero at the back and double the uniform pressure or 11516 lbs at the toe. But even this extreme pressure which is not likely to occur is well within the limits found above.

In order to give the wall a broader

base and prevent the toe ploughing into the clay a trench was excavated and filled with broken stone as described above.

The factors of safety of these walls are small but this is the case in all masonry, and there are many good examples in which they are much smaller than those found above.

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May 1877.