SECTION V

EARTH PRESSURE: STABILITY AND DISPLACEMENTS OF RETAINING CONSTRUCTIONS

SUB-SECTION V a

EARTH PRESSURE AGAINST RIGID VERTICAL WALLS

V a 1

EARTH PRESSURE AGAINST RETAINING WALLS

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AN INVESTIGATION ON A HALF-LARGE SCALE, BY THE HARBOUR BUILDING DEPARTMENT OF THE PORT OF STOCKHOLM ANTHORITY

The nearest reason why this investigation of earth pressure on retaining walls has been made by the harbour building department of Port of Stockholm Authority is the difference between the standard specifications of the State and those of the municipal authorities in Stockholm.

Until the 22nd of May 1945 the specifications of the State prescribed retaining walls to be calculated for earth pressure at rest and independent of the backfilling material, whereas the municipal authorities apply the up to now usual theories of friction for calculating the earth pressure. The earth pressure at rest is to be calculated from the formula $0{,}45\gamma h^2/2$, x) where γ = weight per unit volume (t/m^3), h = the height (m) of the backfilling.

The difference between the pressures thus calculated is essential. For a gravel-filling with an angle of internal friction of about $\varphi = 30$ degrees the earth pressure at rest is about 50 % larger than the active pressure calculated by means of the theory of friction. For a filling of stones from burstings with $\varphi = 45°$, which is very usual in Stockholm, the earth pressure at rest is not less than $2\frac{1}{2}$ times larger than the active pressure.

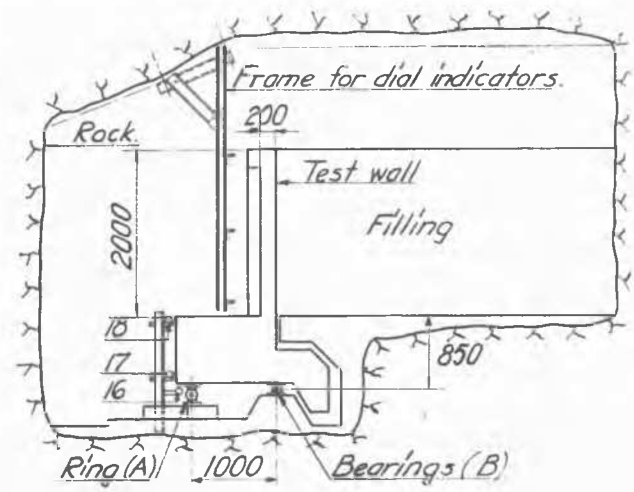
The economical consequences of giving up the classical theories of friction are obvious to everyone, and as the assumptions for the genesis of the earth pressure at rest have been insufficiently investigated, this fact was enough as a motive for the here described tests on a half-large scale.

In 1945 the Harbour building department of Stockholm began to plan such experiments after conferences with the Bureau of the Public Works Department of Stockholm and the Royal Swedish Geotechnical Institute.

The extensive experiments performed by Terzaghi have made clear that the pressure on a retaining wall is a function of the movements of the wall. When the wall is completely immovable the rest pressure will arise. It requires however only a very little movement of the wall in the direction of the pressure to reduce this pressure at rest to an active one.

With our economical resources, 22.000:- sw. crowns, it was not possible to make such arrangements as those of Terzaghi. His experiment wall could be given arbitrary movements at the same time as the pressure was measured.

Instead it was decided to give the wall such a shape, which (according to this stiffness) would give a good correspondence to practically constructed retaining walls. By furnishing the wall with buttresses it is also possible to give it a greater stiffness.



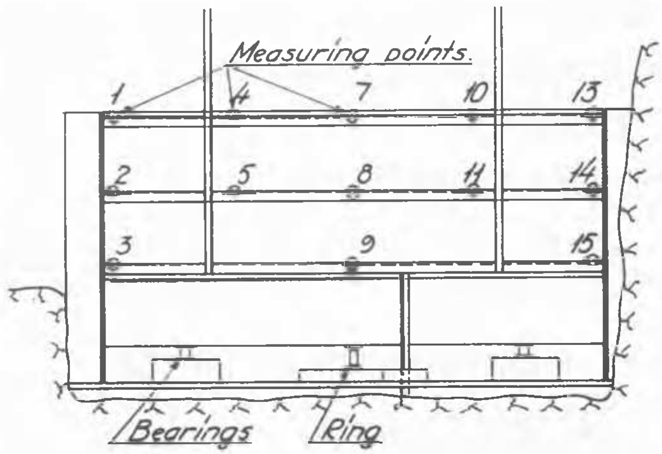
Cross section of test wall

FIG.1

The appearance of the wall is shown in fig. 1. 2 and 3. It is two metres high and 6 metres long and can freely move between the two side walls. The space between the side walls and the retaining wall is covered with cloth, saturated with asphalt emulsion and formed as bellows (fig. 4). As the length is large in relation to the height, there will be very little influence on the measured pressure from the friction along the side walls. Besides no arching effects can reasonably arise. Moreover the sidewall are covered with 0,8 mm thick steel-plates, coated with a mixture of grease and graphit. The influence of friction has been closely investigated as well by tests as in the theory.

The wall is constructed in reinforced concrete and formed as an angle. It is supported in three points, namely two bearings B and the

x) per unit length



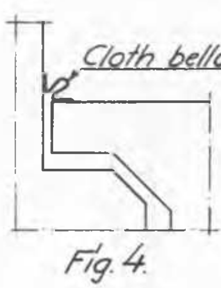
Elevation of test wall

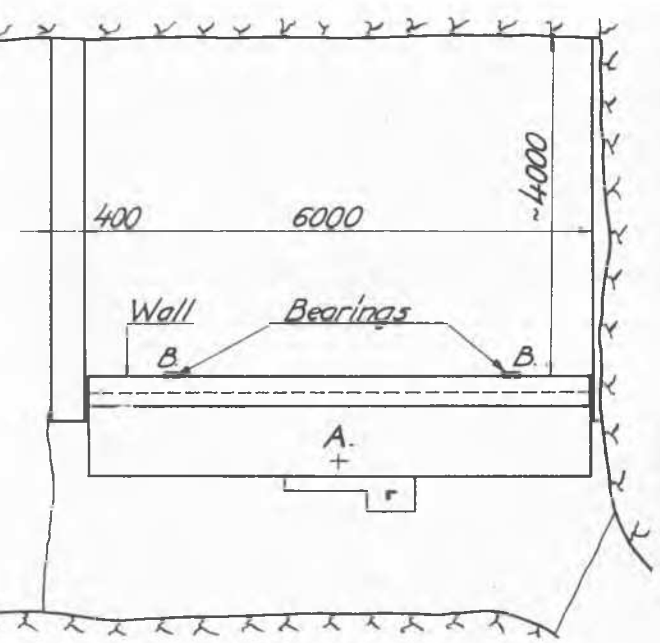
FIG.2

can be taken away. Hereby it is possible to give the wall a movement from the backfill. At the upper edge this movement can be as much as 6 mm.

However, change of temperature has a very great influence on the apparatus. The inner diameter of the ring is 60 mm, and an increase of temperature with 1 degree (Celsius) causes an expansion of about $1{,}2 \cdot 10^{5} \cdot 60 = 7{,}2 \cdot 10^{4}$ mm or 3,6 % of the maximal deviation and about 10 % of the deviation caused by active pressure. It is true that this expansion to some extent will be neutralized by the expansion of the instruments, but as the ring consists of a very thick metal, the expansions will not be synchronous. To eleminate this influence of temperature as much as possible both the ring and the instruments have been enclosed in a well isolated box. An electric thermoelement combined with a Sunvic-thermostat, controlling the temperature within a range of $\pm$ 0,2° C provides for a sufficiently constant heat.

As an extra control the temperature in the box with an accuracy of 0,1° C can be read on





Plan of test arrangements

FIG.4

FIG.3

third point A, fig. 1, 2 and 3, where the instruments have been placed. The bearings have the same twisting axis lying in the plane formed by the inner surface of the wall. Hereby possible forces of friction along the innerside of the wall will give no moment round the axis of the bearings.

The measuring apparatus at A consists of a steel-ring with two "microcators" made at the factory of C.E. Johansson in Eskilstuna, Sweden, fig. 6, 7. They measure the deformation of the ring at its inner surface. For a force of 13 ton the ring will be compressed 0,02 mm and this gives a deviation of 200 points on the instruments. Thus the force can be determined with an accuracy of about 0,065 ton.

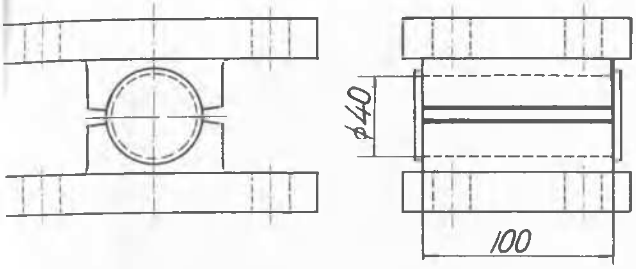
The connection between the deviation on the instruments and the force on the ring has been determined by loading the wall with water-pressure.

Between the ring bearing and its plates there are two 1 mm thick steel plates, which a mercurial thermometer.

The whole establishment is contained in a fence-room blasted in rock. Thus the plinths for bearings and ring are founded directly on the rock and their movements due to varying load will be as small as possible. Another advantage is the very slowly changing of the temperature in such a fence-room.

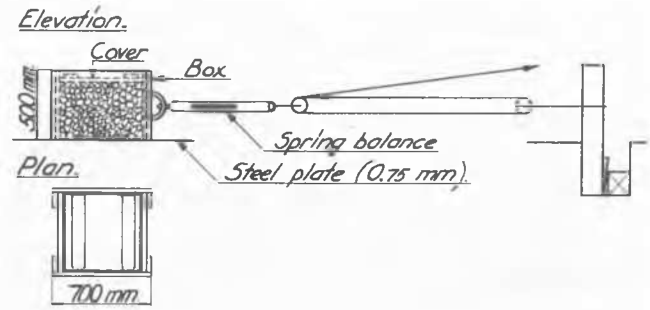
With these arrangements we can measure only the moment on the wall. If as usual the distribution of the pressure is assumed to be triangular, the largeness of the pressure also can be calculated. The investigations of Terzaghi show that the resultant of the pressure will fall in the lower third part point of the height of the wall. In order to diminish the influence of a possible divergence in this respect the bearings have been placed 0,85 m below the floor behind the wall, and thus the resultant gets a rather long heaving arm (fig. 1).

The deflection of the wall is measured



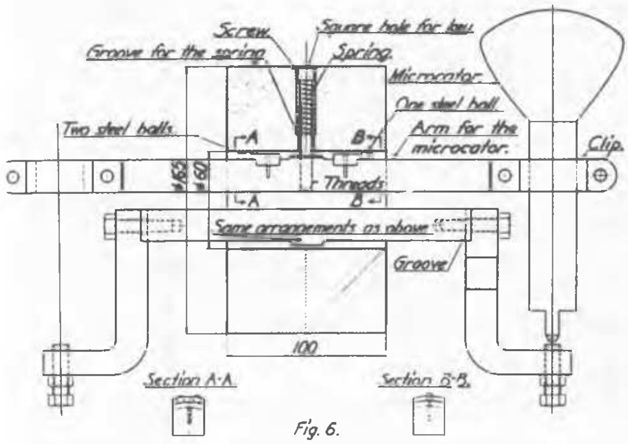
Bearings.

FIG.5



Arrangement for friction tests.

FIG.8



Section of the ring

FIG.6

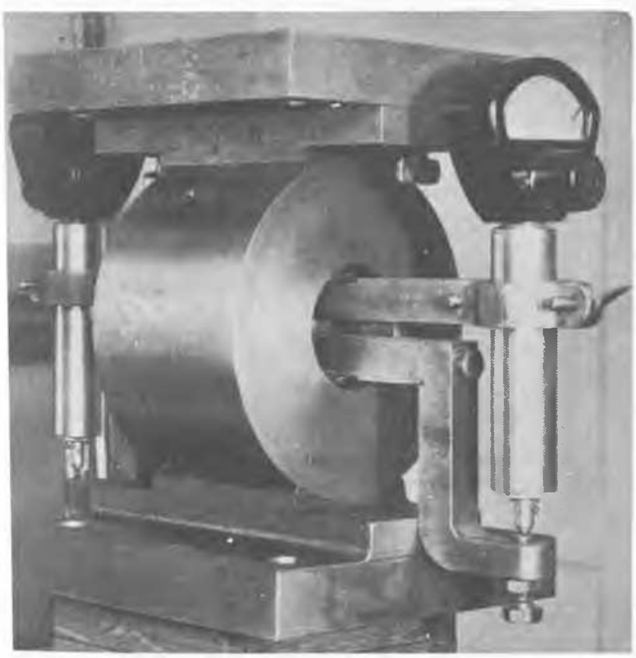


FIG.7

ith an accuracy of 0,01 mm in 16 points shown n fig. 2. In test number 1 and 2 the deflections were not measured in the points nr.16, 7, 18.

FRICTION ALONG THE SIDE-WALLS.

In order to find out the influence of friction along the sidewalls the following tests were made

The friction coefficient for stone material against a steelplate was determined, at first with unprepared plate and then with the plate covered with grease and graphit. The materials investigated were crushed stone (grain size 32-64 mm) and a kind of gravel with nearly round grains (grain size 16 - 32 mm). The apparatus consists of a box without bottom in which the gravel was filled (fig.8) The box was placed on a steel-plate and thus the gravel rested directly on the plate. The cover of the box could slide freely between the sides of the box, and on the top of the cover the weights were placed by which different normal pressures against the plate could be produced.

In one side of the box a springbalance, graduated from 0 to 150 kg, was fastened and in this a block with a fourfold gear. The friction force was determined by successively increasing the tensile force until the first movement of the box could be observed. This was repeated 10 times for each normal pressure and the following values on the friction-coefficient are average values from ten observations.

The testing results are summed up in the table below.

Filling material	coefficient of friction
1) crushed stone - unprepared plate	$\mu = 0,54$
2) crushed stone - greased plate	$\mu = 0,26$
3) round grain gravel - unprepared plate	$\mu = 0,48$
4) round grain gravel - greased plate	$\mu = 0,24$

While the friction coefficient between makadam and plate is only 10 % greater than that between this special gravel and plate, a preparation of the plate with grease and graphit is able to diminish the friction in both cases with about 50 %.

ESTIMATION OF THE INFLUENCE OF FRICTION ON THE MEASURED PRESSURE UPON THE RING.

When calculating active pressure it is assumed that an earth wedge shall be prevented from sliding away. The pressure from the wedge against the side walls is represented by a pyramidical body (fig. 9) and has a largeness of

$$Q = \frac{c}{6} \cdot h^3 tg\,\omega$$

where $\omega = 45^\circ - \varphi/2$,

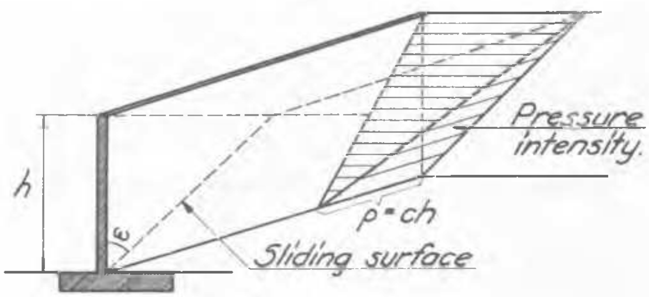


FIG.9

φ = angle of internal friction and $C = \gamma . tg^2 \omega$

If the friction(F) is completely developed it is: $F = \mu Q$

for crushed stones(φ = 45°; γ = 1,7 t/m³) c = 0, 29

for gravel(φ = 33°; γ = 1,8 t/m³) c = 0,53

CALCULATION.

A. φ = 45°.

Active pressure on the wall

$0,29 . 2^2 . 6/2 = 3,48$ ton

Active pressure on the sidewall

$0,29 . 2^3 . 0,414/6 = 0,16$ ton

friction along side wall

$0,26 . 0,16 . 2 = 0,083$ ton

friction in % of the total pressure on the wall $0,083 . 100/3,48 = 2,3$ %.

However, it is the force upon the ring, which is measured and it is therefore the diminution (X_F) (caused by friction) on this force which ought to be compared with the force (X) upon the ring caused by earth pressure.

$X = 3,48 . 1,52 = 5,28$ ton
$X_F = 0,083 . 1,85 = 0,154$ "

and in % we have

$$\frac{X_F}{X} . 100 = 2,9 \%.$$

B. φ = 33°.

In the same way we get

$$\frac{X_F}{X} . 100 = 3,8 \%.$$

The influence on the measured pressure from the friction is consequently of so little importance that it can be neglected.

EARTH PRESSURE.

Test nr 1.

The backfilling material was crushed stones with a grain size of 35 - 75 mm and weight of 1,34 t/m³. The angle of internal friction (40°) was determined by measuring the slope of repose. The manner of filling is shown in fig. 10.

The earth pressure was measured during two months and diminished about 5 %. The coefficient c in the formula $J_a = c\gamma . h^2/2$ was determined to c = 0,22.

Following table shows the deflections of the wall given in 0,01 mm. The measured points are situated as in fig. 2. (tableI)

Test nr 2. Traffic load.

As traffic load were used concrete cubes 0,25 x 0,25 x 0,25 m, filled with cut off pieces of iron. They represented a vertical load of 0,877 t/m². The cubes were placed in rows parallel to and beginning at the wall. The pressure on this increased asymptotic to an upper limit as the number of rows increased. When the cubes covered a surface of about 1,8 x 6,0 m² the pressure did not increase any more. The test was finished when the surface covered was 2,2 x 6,o m2.

The cubes were loaded and unloaded three times. If the measured pressures are assumed to correspond to a uniform load on the wall according to the formula $P_h = C . P_v$ where P_v = vertical load, P_h = horizontal pressure, the found values on the coefficient c were

1:st time	0,216
2:nd "	0,236
3:rd "	0,221

The most remarkable thing at this test was the fact that after the cubes having been

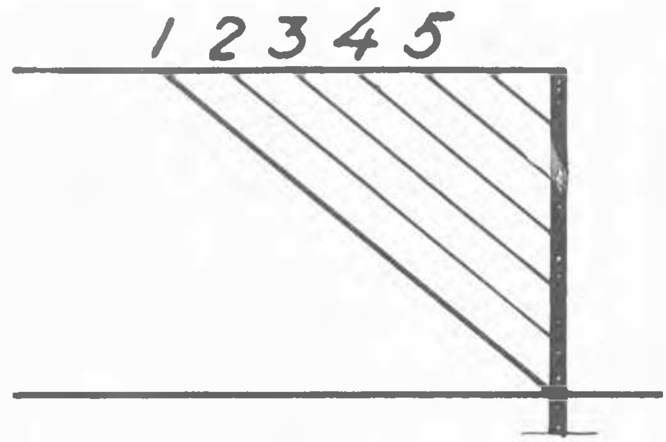


FIG.10

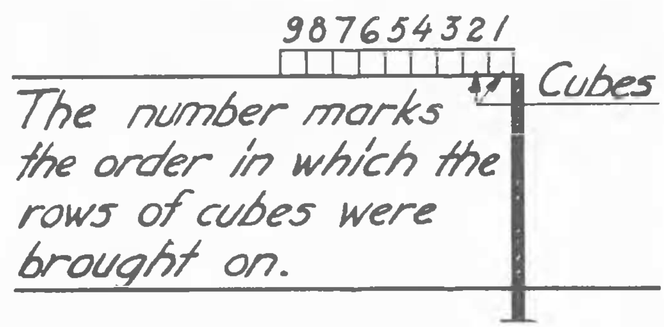


FIG.11

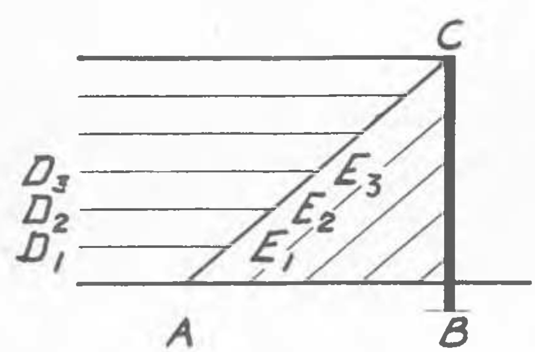


FIG.12

Table I

Point	1	2	3	4	5	7	8	9	10	11	13	14	15	Load
	0	0	0	0	0	0	0	0	0	0	0	0	0	no backfilling
	52	37	20	58	39	63	41	24	63	35	63	47	31	full "
	69	40	22	65	39	66	40	21	68	35	77	45	26	after 1 week
	71	41	23	68	40	71	42	22	68	35	79	47	25	" 2 weeks
	73	44	24	71	44	78	47	22	68	35	79	50	23	" 1 month
	76	47	26	70	48	70	49	21	68	35	79	53	20	" 2 months

Table II

Following table shows the deflections of the wall in 0,01 mm

Point	1	2	3	4	5	7	8	9	10	11	13	14	15	LOad
	0	0	0	0	0	0	0	0	0	0	0	0	0	no load of cubes
	39	28	14	43	28	44	27	14	34		42	30	12	cubes=0,88 t/m^2
	46	29	15	47	31	45	30	14	35		56	30	12	after 1 week
	33	25	14	36	27	36	27	15	31		43	31	22	cubes unloaded
	41	34	21	50	39	52	39	20	34		46	34	21	load for 2nd time
	36	28	20	35	33	32	31	18	29		36	30	21	" brought off
	43	34	23	41	37	38	35	20	28		41	35	21	" for 3rd time
	53	34	24	60	36	33	33	19	28		50	32	19	1 week later
	49	34	26	57	35	29	33	18	25		45	35	21	load brought off

unloaded, about 60 % of the pressure from the cubes remained. In spite of this the pressure on the wall increased only very little when the cubes were brought on for the second and third time. (table II)

Test nr 3.

The arrangement and the backfilling material were unchanged and the filling manner as in fig. 12. The earth wedge ABC was brought on in layers marked in fig. 12, where AC marks the slope of repose. The rest of the filling was brought on in layers parallel D_1E_1, D_2E_2 and so on until full height. The final pressure was $J_a = 0{,}276 \cdot \gamma h^2/2$.

Test nr.4. Traffic load.

Traffic load was applied in the same manner as in test nr 2. Following values on C were found

1:st time C = 0,212
2:nd " 0,228
3:rd " 0,230

The remaining pressure after the first time of loading and unloading was 66 %, after the second time 65 % and after the third time 69 % of the total pressure caused by the cube load.

CONCLUSION.

Test nr 1 shows that in this case the earth pressure against the retaining wall was in average $J_a = 0.22\gamma h^2/2$

According to the classical wedge theory the pressure can be calculated by the formula

$$J_a = tg^2(45^\circ - \frac{\varphi}{2})\gamma h^2/2$$

If $\varphi = 40^\circ$ is substituted we get

$$J_a = 0{,}217 \cdot \frac{\gamma h^2}{2}$$

The agreement between theory and tests is evidently very good. The deflection of the wall at the upper edge at the beginning of the test was 0.60 mm in average and at the lower edge 0,25 mm. Thus the relation between deflection and height of the wall was 0,60/2000 = 1/3300. This deflection is then sufficient to reduce earth pressure at rest to active pressure.

Test nr 3 shows the importance of the manner, in which the backfilling is brought on. The larger pressure is probably caused by some wedge effect from the layers D-E. A later test, not described here, has namely given the same result as test nr 1. The assumptions were the same.

Test nr 2 and 4 also show good agreement with the wedge-theory. It is evident that for walls with analogous stiffness as the test wall the wedge-theory well coincides with real circumstances.

The tests are to be continued, and as said in the introduction the pressure on a wall furnished with buttresses will be examined.

SUMMARY.

When the authorities of the State in Sweden began to prescribe certain retaining walls to be constructed for earth pressure at rest, the municipal authorities decided by means of tests to investigate, if there on a wall of in practice usual stiffness really would be an active pressure or an earth pressure at rest.

The test arrangements consist of a 2 m high and 6 m long retaining wall, which can freely move between two side walls. The wall rests at two bearings, situated in the same plane as the inner surface of the wall, and is in a third point supported by a ring of steel. The deformation of the ring, less than 0,02 mm at maximal load (13 ton), is measured by two "microcators". From the load on the ring

the moment on the wall can be determined. If triangular intensity of pressure is assumed, also the magnitude of the earth pressure can be determined.

Up to now tests have been done with crushed stones of a grain size 35 - 75 mm and an angle of internal friction $\varphi = 40^o$. If the filling was brought on successively against the wall (see fig. 10), the pressure was $J_a = 0,22 \cdot \gamma \cdot h^2/2$. According to the friction theory it would have been $0,217 \gamma h^2/2$. The deflection of the wall was 0,60 mm at the upper edge and 0,20 mm at the lower one. The relation between the deflection at the upper edge and the height of the wall was then 1/3300.

Tests have also been made with load on the filling. If the measured moment on the wall is assumed to be caused by an uniform horizontal pressure on the wall the horizontal pressure was equal to 0,22 times the vertical load. When the load was taken away 60 - 70 % of the pressure caused by the load still remained.

Up to now all the tests have shown that elastic and plastic deflections of the size mentioned above are sufficient to reduce earth pressure at rest to active pressure.

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SUB-SECTION V b

EARTH PRESSURE AGAINST FLEXIBLE VERTICAL WALLS

V b 1 MEASUREMENT OF PRESSURE IN TIMBERING OF A TRENCH IN CLAY

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This paper describes some measurements of the pressure in the timbering of a deep excavation behind a retaining wall in the London Clay.

The plan and section of the wall are shown in figures 1a and b. The wall, which was about 40-ft high, was built in 1901-02. In 1920 serious movement of the wall was noticed and six counterforts were constructed behind the wall. Movement of the wall was thus almost arrested until 1939 when further movements occurred. It was decided to construct a continuous counterfort behind the wall joining four of the previous isolated counterforts and extending beyond them as shown in the plan. The new counterfort was to be 6-ft deeper than the existing wall foundations and was to be constructed in seven sections, each about 25-ft long carried out in the order shown in figure 1a.

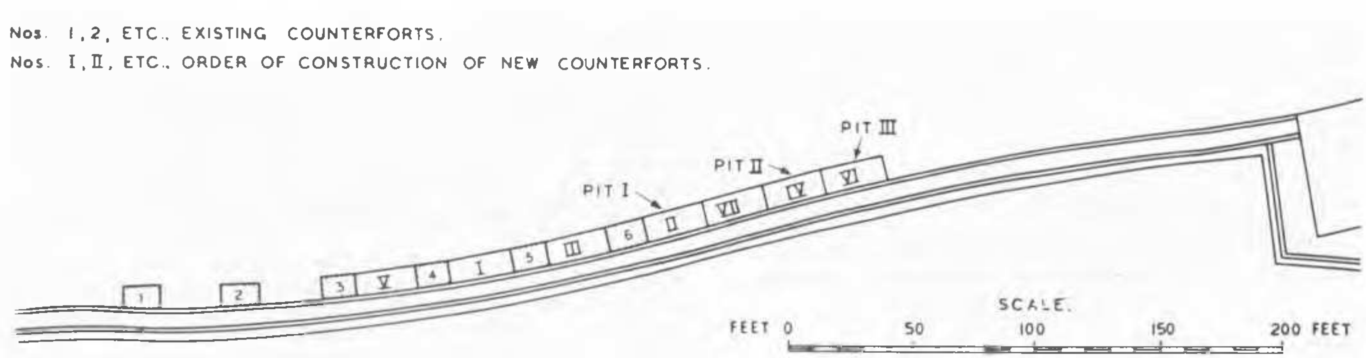
The opportunity was taken to measure the pressure in some of the timber struts supporting three of the excavations.

METHOD OF MEASUREMENT.

One of the conditions laid down by the Railway Company was that any work carried out should not interfere in any way with the Contractor's progress on the job. This ruled out the use of steel struts and elaborate pressure measuring devices.

Preliminary laboratory tests with a surface strain gauge had shown that this method was of no use with timber struts since the drying tensions in the surface of the timber sometimes exceeded the compression due to the applied load. It was decided therefore to attempt to measure the reduction in length of a large length of the strut under applied load. The measurements were made over a gauge length of 5-ft with a micrometer reading to 0.01 mm.

The technique of measurement had been developed at the Building Research Station to measure the shrinkage of brickwork and was applied with one or two minor modifications to the present problem. The micrometer was



Plan of wall

FIG.1a