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Earth Pressures on Walls Subjected to Cyclic Vertical Movement

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SUMMARY This study involves the measurement under laboratory conditions of the earth pressures developed by a moving wall for which the dominant movement is vertical. A dry sand was used as the backfill soil, the earth pressures being observed by means of a number of pressure cells set into the face of the wall. The lateral earth pressures were found to increase following upward wall movement and decrease following downward wall movement. The small lateral wall movement towards the backfill on the upward stroke, which occurred at the same time as the dominant vertical movement, was found to contribute to the earth pressures observed. The magnitudes of the peak lateral pressures developed were found to depend upon the magnitude of the upward wall movement and the number of cycles of movement. The variation in peak earth pressure with magnitude of wall movement was found to be related to the development of wall friction and approximate agreement was obtained between the observed and calculated passive pressures.

1 INTRODUCTION

There have been numerous reported observations of high cyclically varying earth pressures that develop behind walls of navigation locks and dry dock structures. Sinyavskaya and Pavlova (1971) observed two types of cyclical earth pressure changes against the wall of the Volgograd lock over a ten year observation period. One type was caused by seasonal temperature changes with the maximum earth pressure developing during the summer and caused by wall movements towards the backfill of the order of 2 mm. The other type was caused by emptying and filling of the lock, with the maximum earth pressure caused by filling, which produced wall movement toward the backfill also of the order of 2 mm. The observed peak earth pressures exceeded the design pressures (earth pressure at rest) by a factor of more than 3.

Earth pressure at rest was also the basis of a wall design used for the U frame Port Allen lock (Kaufman and Sherman, 1964). For the lock empty, the coefficient of earth pressure at rest (K_o) used for design was 0.5. For the lock filled with water the value of K_o used varied from 1.0 near the top of the wall to 0.5 at the bottom of the structure. Observed earth pressures were in reasonable agreement with design values for the lock empty but generally much less than the design values for the lock full.

With the Votkin lock, Burmistrov and Kotenkov (1967) found that while the total lateral force on the lock wall increased upon filling, the earth pressure actually decreased at the bottom of the wall and increased at the top. Upon emptying, the earth pressure decreased at the top of the wall and increased at the bottom.

Smoltczyk et al (1977) observed cyclical earth pressure changes against a ship hoist wall at Luneburg caused by seasonal temperature fluctuations. They also found a gradual increase in earth pressure with time over a period of several years. This gradual increase in earth pressure was also observed by Mikhailov and Avdeeva (1973) from a study of data on locks on the Volga - Don canal, the Volga - Baltic canal and the Moscow canal. In some of the locks they found that the lateral earth pressure increased in winter up to almost twice the design pressure when the lock was emptied, in contrast to observations elsewhere and in spite of the wall deflecting away from the backfill. This phenomenon of a pressure increase in winter when the lock was emptied was also noted by Moshkov (1974) on the Votkinsk lock. He also observed that emptying the lock caused the structure to rise (movements 4 - 7 mm) and he suspected that this vertical movement was the main reason for the rise in earth pressure. Moshkov found that the observed winter pressures were of the same order as the passive pressures calculated with the Müller - Breslau equation.

In an attempt to provide a better understanding of the response of lateral earth pressure to wall movements in which the motion is dominantly vertical, an experimental laboratory investigation was undertaken. It was also hoped that the results of this study would help resolve some of the apparently conflicting field observations mentioned above.

2 EXPERIMENTAL DETAILS

A series of tests were carried out in which the lateral pressures generated against a vertically moving retaining wall were observed. The retaining wall arrangement, which is illustrated in Fig. 1, consists of a moveable measuring wall connected by nine pin ended rods to a fixed wall. The measuring wall of machined aluminium was supported on four helical springs, the deflection of which provided a measure of the transmitted vertical force. The measuring wall was moved upwards by means of a water jack on the underside of the wall. Downward movement was effected by means of a pneumatic loading unit mounted above the wall. The upward movement was accompanied by a slight movement of the wall towards the backfill. For the purposes of illustration this motion is shown in an exaggerated form in Fig. 2. This also shows that the mobilized earth pressure acting on the moving wall would tend to act in a downward direction. The horizontal component of the motion was included to simulate the movements of the prototype walls discussed above. The outer (backfill) faces of most of the prototype walls discussed sloped towards the backfill in

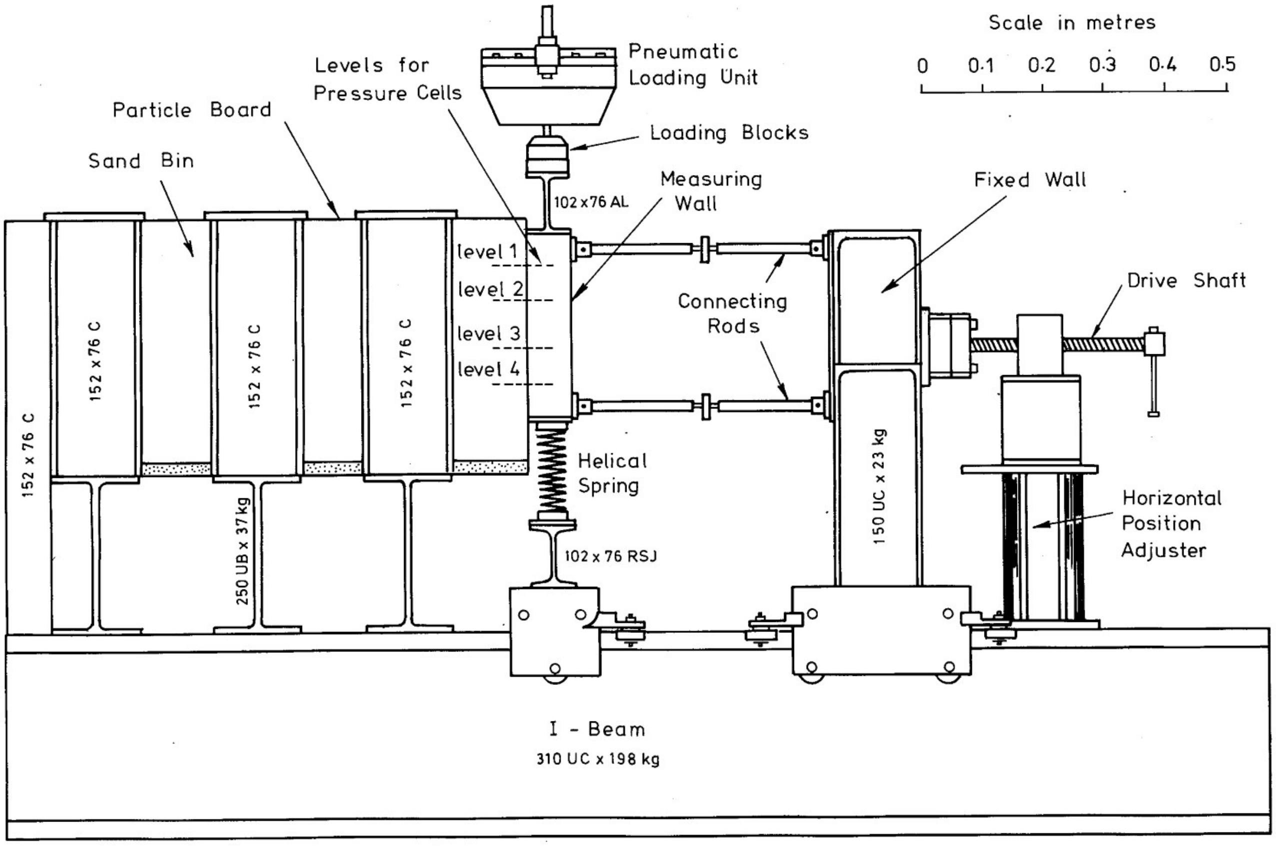

Figure 1 Retaining Wall Arrangement

a downward direction. This means that as the wall rose following emptying of the lock there would be a horizontal component of motion of the wall towards the backfill. The relative magnitudes of the horizontal and the vertical motions of the measuring wall are shown in Fig. 3.

A dry sand was used for the backfill material, the characteristics of which are given in Table I.

TABLE I

SAND PROPERTIES

Particle Density	2.63 gm/cm^3
Grain Size Distribution:	
Percent passing	0.6 mm = 7
Percent passing	0.8 mm = 42
Percent passing	1 mm = 80
Maximum dry density	= 1.6 Mg/m^3
Minimum dry density	= 1.4 Mg/m^3
(according to AS. 1289)	
Shearing Resistance (at density of 1.57 Mg/m^3):	
Peak angle	42°
Ultimate angle	37°

Pluvial compaction of the sand was used to produce a relatively uniform bin of sand for each test. This technique has been described by Jacobsen (1976) and Piper (1977) among others, and involves raining jets of sand from a certain height. The sand jets are then dispersed by passing through a wire mesh before finally falling into the receiving bin. This procedure can produce uniform dense sand deposits, the average density in this study being 1.57 Mg/m^3.

Lateral earth pressures were measured by means of

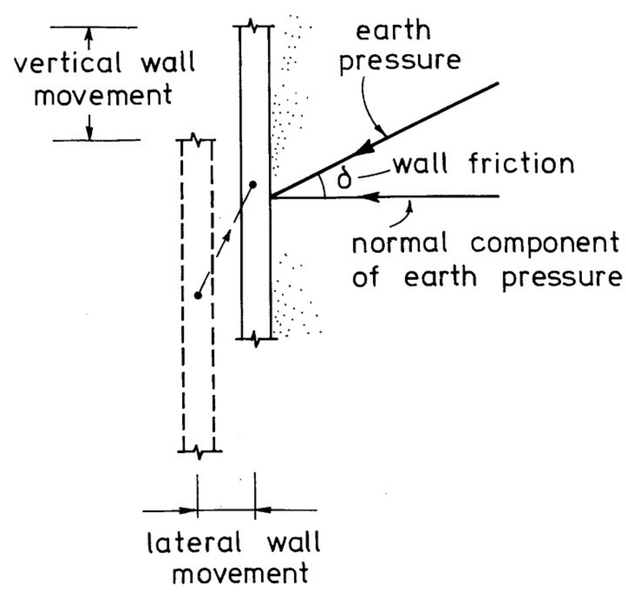

Figure 2 Components of Wall Movement

eight Tyco AB pressure transducers which were mounted flush with the face of the measuring wall at the four levels indicated in Fig. 1. The transducers were connected to two six channel Hottinger bridges, from which output signals were transmitted to an Arlunya Data Logger. The data was recorded and stored on paper tape. The transducers were calibrated in contact with sand and this calibration was checked after each test. Special tests were devised

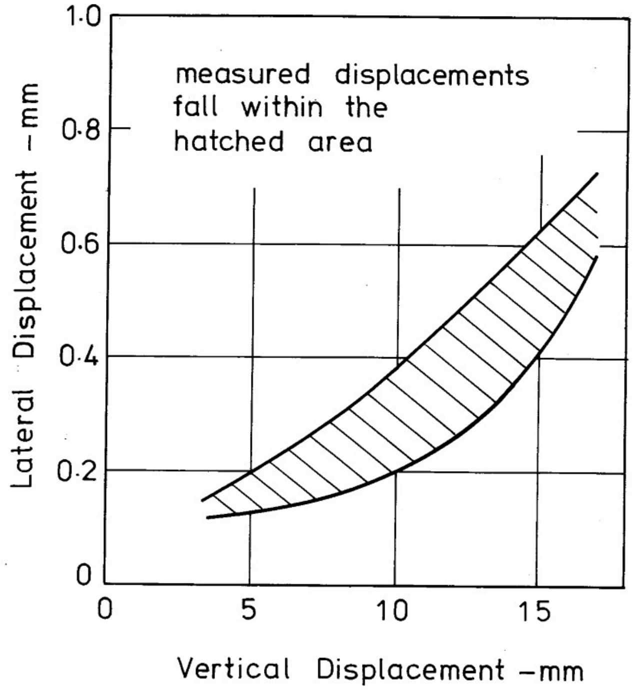

Figure 3 Measured Lateral Wall Movements

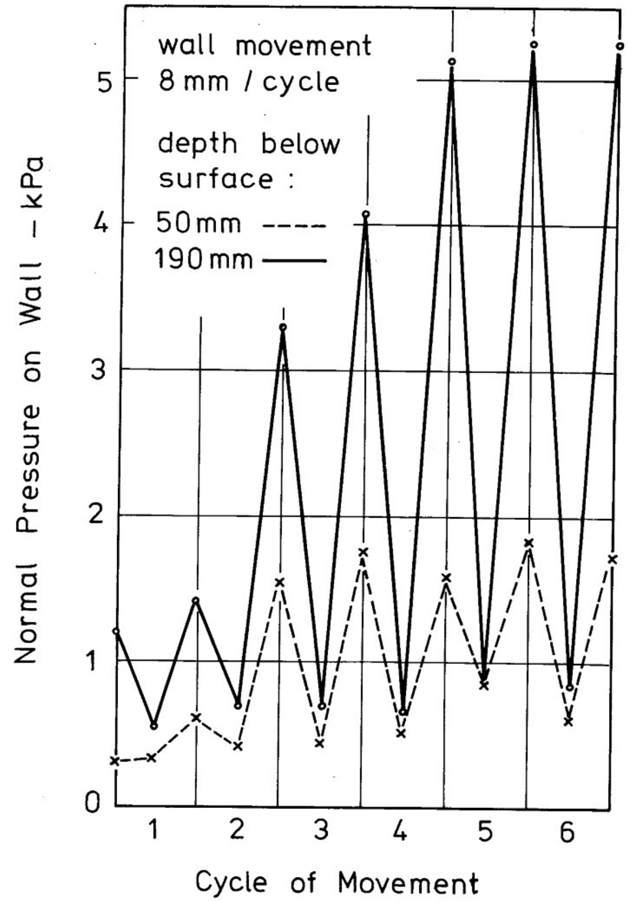

Figure 4 Typical Pressure Cell Readings

to confirm that the transducers were not sensitive to shear stress across the face of the diaphragm.

3 EARTH PRESSURE VARIATIONS

The lateral earth pressures were observed as the wall was subjected to cyclic downward and upward movements. The range of amplitudes (peak to peak) of movement varied from 4 mm to 16 mm which covered the range of reported movements of docks and lock structures. Each test was performed for a constant value of the displacement amplitude, the cycling being continued for about fourteen cycles.

As illustrated in portion of a typical pressure record in Fig. 4 the peak earth pressure was recorded when the wall was in the upper position of the cycle. This behaviour is not unexpected when it is considered that the wall moved toward the backfill on the upward portion of the cycle as shown in Figs. 2 and 3. Fig. 4 also shows that the peak earth pressure rapidly increased during the first few cycles of movement and then exhibited much less variation for the remainder of the test. This behaviour was observed in every test.

The tendency toward development of passive pressure as a result of the purely horizontal wall movement towards the backfill is insufficient to explain the high earth pressures recorded as illustrated in Fig. 4. Tests were carried out in which the wall was moved horizontally, with no vertical motion towards the backfill. The results, shown in Fig. 5, demonstrate that the pressure increase resulting from a purely lateral movement of about 0.2 mm (corresponding to 8 mm vertical displacement (Fig. 3)) was approximately 0.5 kPa at level 3 and 0.1 kPa at level 1. These figures are significantly smaller than the values plotted in Fig. 4. In all tests it was found that the normal pressures developed by purely lateral wall movements were much smaller than those developed with wall movement dominantly vertical, but with the same magnitude of lateral motion.

The effects of magnitude of vertical wall movement on peak lateral pressures are shown in Fig. 6. Here the peak pressures recorded at a particular level have been averaged over the last five cycles of wall movement. The results show that as the amplitude of vertical wall movement increased from 4 mm to 16 mm the average peak pressures decreased significantly. An explanation of this behaviour can be found to be associated with changes in angles of shearing resistance (ϕ) and wall friction (δ).

A number of tests were carried out to measure the average angle of wall friction, the value obtained being 30°. From measurements of forces acting on the vertical measuring wall during the earth pressure measurements it was possible to estimate the average angle of wall friction following upward wall movement. These estimates indicated that the wall friction angle (δ) of 30° applied only to small amplitudes of wall motion and as the wall displacement amplitude increased the value of δ also increased. The maximum value of δ would be equal to the angle of shearing resistance (ϕ). Direct shear tests showed that the peak angle of shearing resistance (42°) was mobilised at small displacements so this value of ϕ should be applied to earth pressures calculations for small amplitudes of wall movement only. For the larger magnitudes of wall movement the ultimate angle of shearing resistance (37°) would be more applicable.

Passive pressure calculations using ϕ = 42° and δ

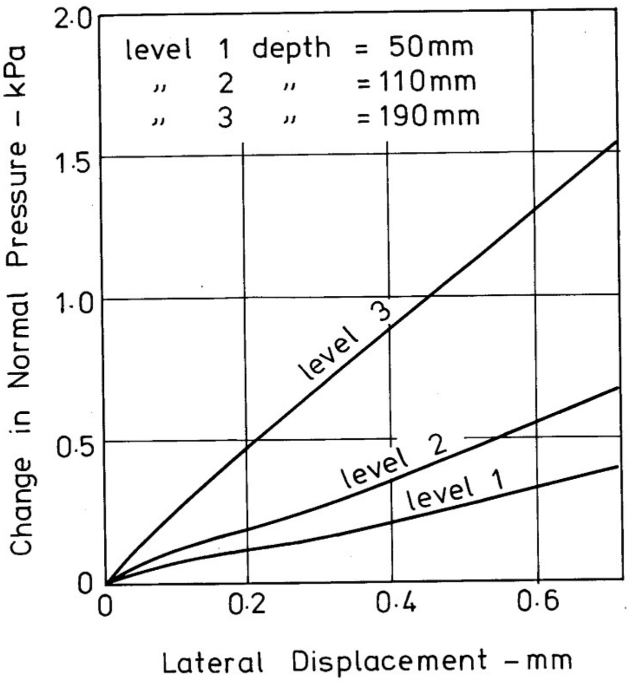

Figure 5 Pressure Change Caused by Lateral Wall Movement

= 30° were carried out by means of the Coulomb expression which is identical to the Janbu (1957) expression for wall friction acting in the direction shown in Fig. 2. The theoretical passive pressure coefficients are shown in Fig. 7. The Caquot and Kerisel (1948) values are lower than the Coulomb values for $\delta = \phi$. Fig. 7 shows that the passive coefficient (K_{PN}) is sensitive to values of δ when $\delta \neq \phi$ but is much less sensitive to changes in δ for the case of $\delta = \phi$. The calculated Coulomb passive pressures, shown on the left side of Fig. 6 show reasonable agreement with observed peak pressure except for the level 1 pressure observations.

Passive pressure calculation for $\phi = \delta = 37°$ are shown on the right side of Fig. 6 and show approximate agreement with observed peak pressures at large amplitudes of wall movement.

4 CONCLUSIONS

1. Observed pressures on a wall moving dominantly in the vertical direction increased following upward movement, the peak pressures increasing significantly over the first few cycles of movement.
2. The average peak pressures after about 10 cycles of movement were observed to decrease as the amplitude of wall movement increased.
3. These observed peak pressures were approximately equal to calculated Coulomb passive pressures if due consideration was given to the effect of wall movement on mobilized angles of shearing resistance and wall friction.

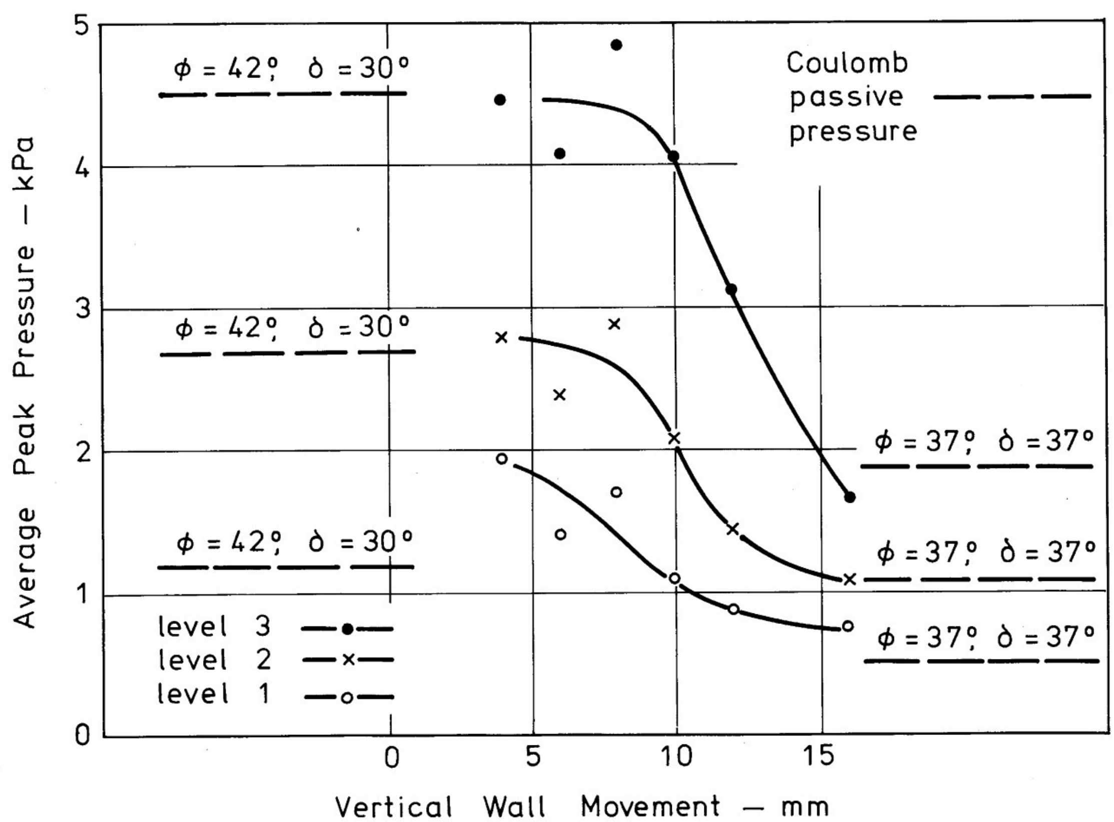

Figure 6 Average Peak Pressure over Last Five Cycles

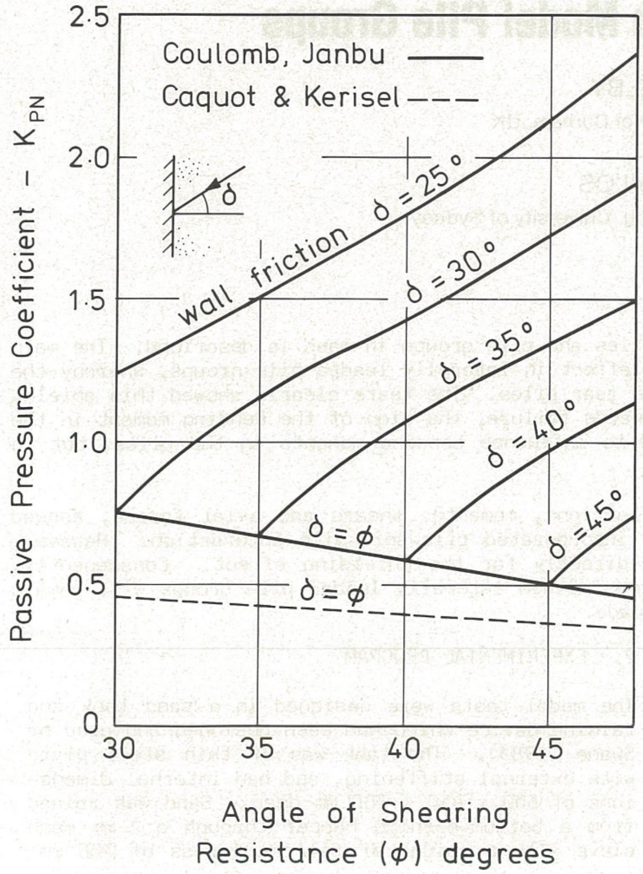

Figure 7 Effect of δ and φ on the Passive Coefficient

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