The Residual Lateral Pressures Produced by Compacting Soils

Les Pressions Résiduelles Latérales Causées par les Sols Compactés

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Summary

The lateral pressures developed by soil compaction which remain after the compaction has been completed have sometimes produced excessive deflections in earth-retaining structures. Laboratory tests made in a 4 in. diameter cylinder indicate that the residual pressures in clay increase with increasing compactive effort and decrease with increasing moisture content. Similar tests in sand indicate little relation between compactive effort, moisture, and residual pressures. Field tests on clay compacted behind a relatively rigid wall show that a compacted clay may develop pressures many times greater than the same clay uncompacted. Similar tests on a sand show that the residual pressures may exceed the at-rest and can be several times greater than the pressures in the uncompacted sand. The residual pressures in the sand did not change appreciably with time after the compaction work was complete; the residual pressures in the clay decreased somewhat with the passage of time.

Sommaire

La pression latérale développée dans le sol par le compactage et qui reste après l'achèvement du compactage donne l'impression de produire une flèche excessive dans les structures de soutènement. Des expériences de laboratoire dans un cylindre de quatre pouces de diamètre indiquent que plus le compactage augmente, plus les pressions résiduelles dans l'argile augmentent, et que plus la teneur en eau augmente, plus les pressions résiduelles diminuent. Des expériences semblables pour le sable indiquent peu de relations entre le compactage, le teneur en eau et les pressions résiduelles. Des expériences sur l'argile rendue compacte derrière un mur de soutènement relativement raide montrent que les argiles rendues compactes peuvent développer des pressions plusieurs fois plus grandes que la même argile quand celle-ci n'est pas rendue compacte. Des expériences semblables sur le sable montrent que les pressions résiduelles dépassent les pressions statiques au repos et sont plusieurs fois plus grandes que les pressions dans un sable qui n'est pas rendu compact. Les pressions résiduelles dans le sable et dans l'argile ne changent pas beaucoup avec le temps après l'achèvement du travail de compactage.

Introduction

Most of the theoretical and experimental studies of lateral earth pressure have been concerned with the pressures developed by undisturbed soils, or by soils dumped or loosely placed against a structure. In some situations, however, a loose backfill will gradually settle under its own weight or that of loads imposed upon it. In order to eliminate this settlement many designers require that backfills which support pavements, floors or foundations be compacted in the same way as other critical fills.

Unfortunately, the compaction of backfills has sometimes been accompanied by excessive deflection of the structures. This has been blamed on the lateral pressures developed by the soil compaction, but the blame has been based purely on circumstantial evidence. Only limited information is available on the magnitude of the pressures developed by soil compaction. The lateral pressures produced by vertical pressures on soils confined within closed chambers and the lateral pressures developed by loads on backfills have been studied at some length (Terzaghi, 1920, 1925; Tschebotarioff, 1951; Spangler, 1938; Feld, 1940; U.S.W.E.S., 1955). However, these conditions are only indirectly related to the lateral pressures produced by compaction.

Tests have been conducted by the Road Research Laboratory in Great Britain (Whiffin, 1954) to determine experimentally the pressures produced by various soil compacting devices. These tests were concerned with the pressures produced during the period of compaction and in the near vicinity of the compacting devices. As far as the author can determine there are no published data on the lateral pressures remaining in the soil after the compaction is completed. Since it is the practice of contractors to brace soil retaining structure during the compaction of backfills, the pressure remaining in the soil after compaction (although undoubtedly smaller than the pressure produced during compaction) can be a critical factor in the deflection of the structure. It was the purpose of this investigation to determine the magnitude of the residual pressure produced by soil compaction and to establish some of the factors which influence it.

Theoretical Considerations

Our present knowledge of earth pressure behaviour indicates that the soil pressures produced by soil compaction depend on at least three factors: the properties of the soil, the dimensions of and the pressure produced by the compaction device, and the deformation of the structure retaining the soil. If soil is loosely placed behind an unyielding structure, the earth pressure p_l at a depth z in a soil having a unit weight of γ is given by the expression

$$p_l = K_0 \gamma z \qquad \ldots\ldots (1)$$

where K_0 is the coefficient of earth pressure at rest. If a uniform pressure of p_v is applied over the entire surface of this soil mass in order to produce compaction, the lateral pressure will become

$$p_l = K_0(\gamma z + p_v) \qquad \ldots\ldots (2)$$

In reality, the structure will probably yield or deform outward. In this case the elastic deformation of the soil mass will bring about a reduction in p_l. The limit of the reduction in p_l will be reached when the soil mass shears—the active state.

Instead of a uniform pressure over an entire backfill, modern compaction methods make use of a relatively high pressure or impact force applied over a limited area. In this case the lateral pressure immediately beneath the compaction device will probably be equal to that given by equation 2, but at other points within the backfill the pressure will be considerably less. If the backfill is well compacted in layers, probably every part of the soil mass will at some time sustain a lateral pressure equal to that of equation 2, but unless the compaction device is very large compared to the surface area of the backfill the average lateral pressure will be smaller, approaching the lateral pressure remaining in the soil after compaction is complete.

The mechanical process by which a vertical pressure is converted to a horizontal pressure within a fragmental mass is not clearly understood. In an elastic material the coefficient of earth pressure at rest, K_0, is related to Poisson's ratio by the expression:

$$K_0 = \frac{\mu}{1 - \mu} \quad \ldots\ldots (3)$$

but this expression merely translates the uncertainty into other terms. If the soil mass is assumed to be made up of individual incompressible particles, compaction must take place by a movement of the particles across one another. If the direction of this movement makes an angle of β with the direction of p_v, and if the angle of friction between the particles is ψ as shown in Fig. 1a, then the coefficient of earth pressure at rest may be derived by the laws of statics:

$$K_0 = \frac{p_l}{p_v} = \frac{\tan(\beta - \psi)}{\tan\beta} \quad \ldots\ldots (4)$$

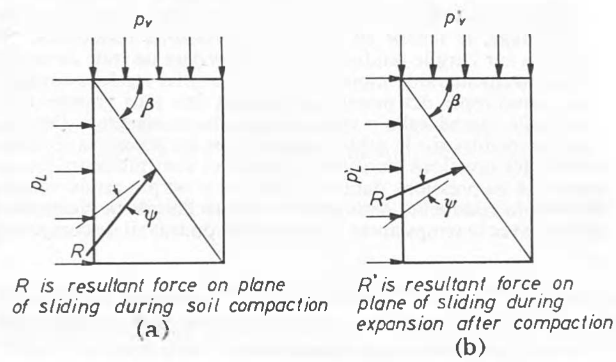


Fig. 1 Mechanism of residual lateral pressure in a fragmental material

Mécanisme de pression latérale résiduelle dans une matière fragmentaire

If the vertical compacting pressure is reduced to p'_v then the soil tries to recover its original volume. In doing so, the frictional force on the plane of movement reverses as shown in Fig. 1b, and the ratio of the horizontal to the vertical pressure becomes

$$K'_r = \frac{p'_l}{p'_v}\frac{\tan(\beta + \psi)}{\tan\beta} \quad \ldots\ldots (5)$$

where p'_l is the residual lateral pressure and K_r is the coefficient of residual pressure against an unyielding structure.

In a soil having cohesion the mechanism is more complex. The friction developed during compaction probably remains as an intrinsic pressure (cohesion) but how much of it remains can only be guessed.

Friction developed between the soil and structure may have its influence on the residual lateral pressure. During the process of compaction the soil moves downward against the structure, developing friction. When the compacting pressure is released, the upward movement is restricted by friction and full expansion cannot take place. This tends to maintain the lateral pressure at a higher level immediately adjacent to the structure.

Obviously if the structure deforms under the action of the lateral pressure, the residual lateral pressure will be reduced. The limiting minimum for this condition will be produced when the soil shears—again the active state.

These brief simplified analyses lead to the following conclusions:

(1) Residual lateral pressures are of importance primarily when the structure does not deform sufficiently to establish active earth pressure.

(2) The residual lateral pressure is a function of the vertical pressure remaining on the soil after compaction and is related to Poisson's ratio.

These served as a guide to the programme of experimental work.

Confined Tests

A laboratory investigation was undertaken to determine the residual pressures produced by compaction of soil in a 4 in. diameter cylinder or cell. The device used is similar to the lateral Earth Pressure Meter developed at Princeton University (TSCHEBOTARIOFF, 1951). The cylinder, Fig. 2, is made of thin steel with narrow slots cut in the side perpendicular to the cylinder axis. Electric SR–4 strain gauges 6 in. long are mounted on the cylinder between the slots and these measure the lateral pressure by the strain in the cylinder walls. The cell was calibrated by subjecting it to internal air pressure confined within a thin rubber membrane.

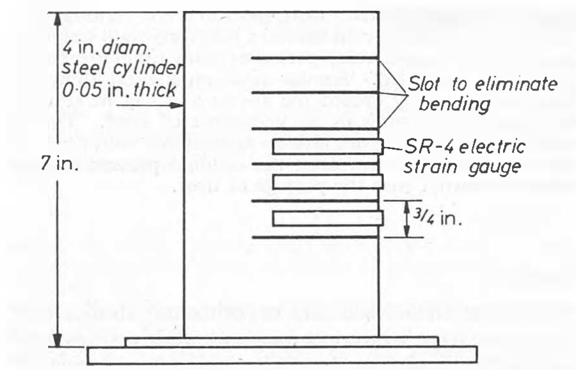


Fig. 2 Test cylinder for determination of lateral earth pressures under confined conditions

Cylindre d'essai pour la détermination des poussées latérales des terres dans une enceinte rigide

The soils used in the testing programme are described in Table 1.

Table 1

Soil description	*Effective size* mm	*Uniformity coefficient*	*Liquid limit*	*Plastic index*
Red inorganic sandy, silty clay	—	—	41	14
River sand: medium-fine subangular quartz	0·26	1·8	—	—
Ottowa sand: medium, uniform rounded quartz	0·6	1·3	—	—
Glacial gravel: well graded silty sandy rounded gravel	0·1	15	—	—

These soils were compacted in the cylinder in layers from 1½ to 2 in. thick. Various moisture contents were used, ranging from air dry to the Standard Proctor Optimum. Both static and impact (dynamic) compaction were employed. The static employed a 4 in. diameter piston and pressures of 425 and 850 lb./sq. in. with a few others for comparison. The impact or dynamic compaction employed 2 in. diameter hammers of the type used for the standard soil compaction tests in the United States: a 5·5 lb. hammer falling 12 in., and a 10 lb.

hammer falling 18 in. In each case 25 hammer blows were used on each layer compacted in the cylinder.

The results of the tests on the medium-plastic clay are shown in the graphs, Figs. 3 to 6 inclusive. The results for both static and dynamic compaction indicate that the residual pressures become less with increasing moisture content, and that they fall off sharply at a moisture content in the neighbourhood of

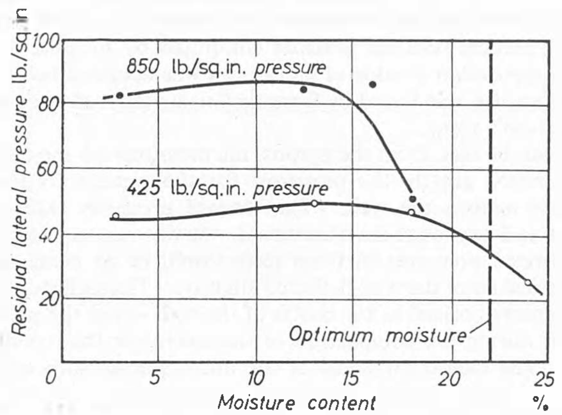


Fig. 3 Relationship between soil moisture and residual lateral pressures for the red sandy silty clay with static compaction under confined conditions

Relation entre le teneur en eau du sol et les pressions latérales résiduelles pour l'argile rouge qui contient du sable et du silt avec compactage statique dans une enceinte rigide

the Standard ASTM compaction test optimum. Measurements of densities after the soils were compacted show that the 425 lb./sq. in. static and the light impact compaction produced approximately the same weight per cu. ft. The test curves, therefore, show that impact compaction produced smaller residual pressures for a given degree of compacted density than did the static compaction. The graph of residual pressure

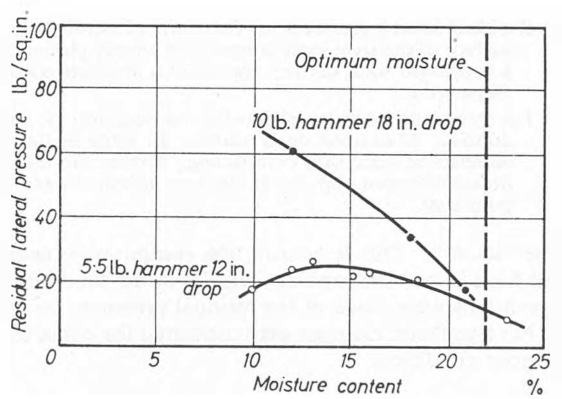


Fig. 4 Relationship between soil moisture and residual lateral pressures for the red sandy silty clay with impact compaction under confined conditions

Relation entre le teneur en eau du sol et les pressions latérales résiduelles pour l'argile rouge qui contient du sable et du silt, avec compactage par damage dans une enceinte rigide

versus impact compactive effort, Fig. 5, shows a linear relationship. Since previous research indicates that soil density increases at a decreasing rate with increasing compactive effort, it follows that the residual pressure increases at an increasing rate with increases in density. These tests certainly show the effect of moisture on the behaviour of the clay in compaction. An increasing moisture content increases the at-rest pressure as is shown by Poisson's ratio curve, Fig. 6, but at the same time the residual lateral pressure decreases. This is to be expected, since at moisture contents just above the optimum a compacted soil is nearly saturated and so acts somewhat like a viscous fluid.

The cylinder tests on the cohesionless soils showed only small residual pressures or none at all, as can be seen by Fig. 7. This is in agreement with equation 5 which shows that there must be a vertical pressure on the soil in order to have a residual

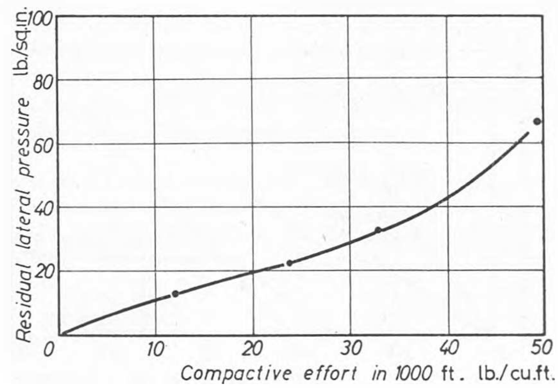


Fig. 5 Relationship between compactive effort and residual lateral pressure for the red sandy silty clay at a moisture content of 14 per cent with impact compaction under confined conditions

Relation entre l'effort de compactage et la pression latérale résiduelle pour l'argile rouge qui contient du sable et du silt à un teneur en eau de 14 pour cent, avec compactage par damage dans une enceinte rigide

lateral pressure. Those pressures which were measured were possibly developed by the friction along the walls of the cylinder or by capillary tension action on the grains which produced apparent cohesion. In all the cases Poisson's ratio was found to vary between 0·3 and 0·4 for the cohesionless soils, with grain shape and moisture having little effect.

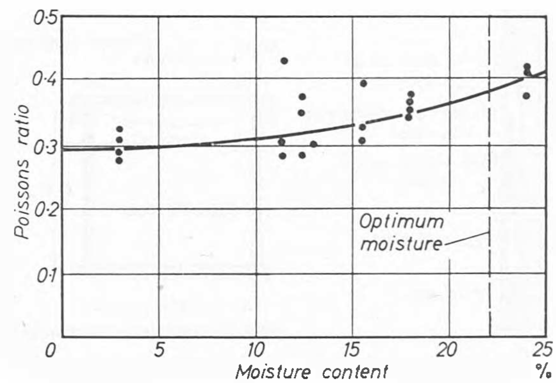


Fig. 6 Poisson's ratio for the red sandy silty clay at varying moisture contents with static compaction

Coefficient de Poisson pour l'argile rouge qui contient du sable et du silt avec teneurs en eau diverses, avec compactage statique

Pressure Cells

Measurement of residual pressures against actual structures requires a pressure measuring device or cell. Most of the cells now in use, such as those developed by the U.S. Waterways Experiment Station (U.S.W.E.S., 1955), have been designed for great accuracy and permanence. In this investigation, however, the need was for a sensitive cell which would measure small residual pressures and which would be cheap enough that it could be abandoned after a few measurements were made. The final design, Fig. 8a, consists of an aluminium disc, 4 in. in diameter, with an aluminium diaphragm $\frac{1}{16}$ in. thick. The pressure is measured by the deflection of the diaphragm under load, and the deflection in turn is measured by a pair of SR–4 electric strain gauges. The cells were waterproofed before use in damp soils.

The cells were individually calibrated using the chamber shown in Fig. 8b. Each cell was placed on a concrete base and covered with the same soil used in the backfill. A thin rubber membrane was placed over the soil and air pressure introduced above the membrane and below the chamber cover to provide a uniform loading. Separate calibration curves were made for both loading and unloading, because considerable hysteresis was found, depending on the type of soil and its moisture. Tests made at intervals of several weeks on some of the cells showed little or no change in calibration.

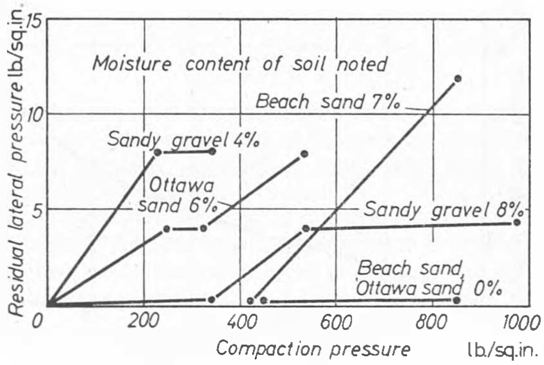
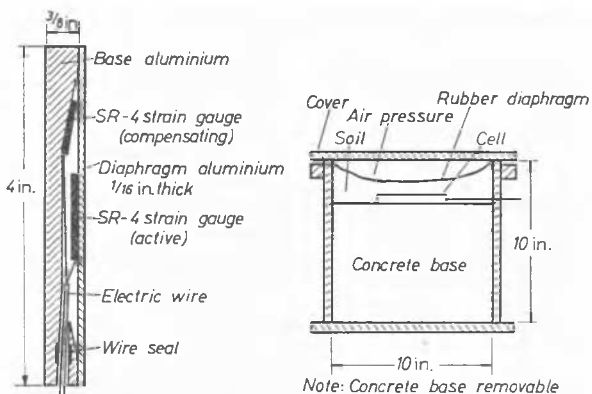


Fig. 7 Relationship between soil moisture and residual lateral pressures for three cohesionless soils

Relation entre la teneur en eau du sol, l'effort de compactage, et les pressions latérales résiduelles pour les sols sans cohésion



(a) *Cross section of cell* (b) *Calibration chamber*

Fig. 8 Earth pressure cell and calibration chamber

Cellule de pression du sol et chambre d'étalonnage

Field Tests in Sand

Field tests were made employing the same river sand as used in the confined tests. A concrete lined test pit 5 ft. deep, 5 ft. wide and 8 ft. long was available from other research. The walls of the pit were 4 in. thick and backed by stiff clay. Pressure cells were fastened to the pit walls using plaster. Sand was placed in the pit in 4 in. thick layers and thoroughly compacted using a pneumatic backfill tamper. Two different moistures were employed; air dry, at approximately 2 per cent water content; and moist at approximately 14 per cent water content. For comparison, the tests were re-run with the same soils dumped in the pits without compaction. The results of the tests, shown in Fig. 9, show the lateral pressures after completion of all compaction. On the same graphs are shown three straight lines: one is the active soil pressure computed by the formula

$$p_a = \gamma z \tan^2 \left(45 - \frac{\phi}{2}\right)$$

where ϕ is the angle of internal friction of the sand; the second is the at-rest pressure computed by formula 1 and the third is the theoretical residual pressure computed by formula 5. In this computation a value of 60 degrees was assumed for β, and the value of ψ was found by formula 4 using the measured value of Poisson's ratio.

As can be seen from the graphs, the pressures for the tamped soils exceed greatly the pressures for the same soils loosely dumped against the wall. The tamped pressures exceed the at-rest and approach the theoretical. It was not expected that the tamped pressures in these tests would be as great as the theoretical since the wall deflected slightly. This deflection was particularly noticed at the centre of the wall where the pressure fell off during the compaction of the soils near the top of the wall. The lateral pressures of the uncompacted soils are less than the 'active'. This is because the computation neglected the wall friction and the capillary tension in the sand moisture.

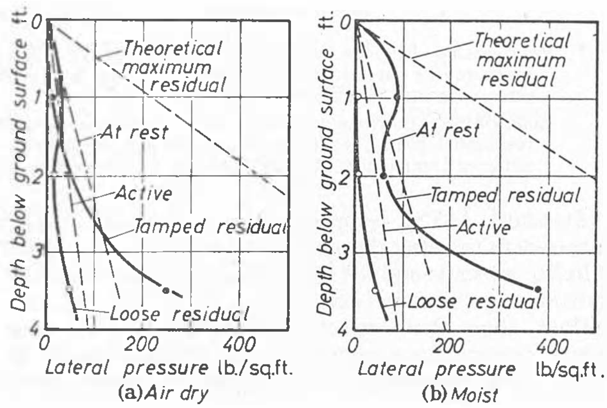


Fig. 9 Residual lateral pressures as functions of depth below the surface of the river sand tamped and loosely placed behind a supported wall: (a) dry and (b) at a moisture content of 14 per cent

Les pressions latérales résiduelles en fonction de la profondeur au-dessous de la surface du sable fluvial rendu compact et placé sans compactage, derrière un mur raide de soutènement, (a) sec et (b) avec teneur en eau de 14 pour cent

Observations were made of the residual pressures for several days. No significant changes were measured for either the dry or the moist condition.

Field Tests in Clay

Field tests were made employing a sandy silty clay similar to that used in the confined cell tests and a moisture content of 18 per cent. A concrete retaining wall 8 in. thick and 6 ft. high was available on a construction job in Atlanta. This was supported by a footing at the bottom and concrete floor at the top. Four series of tests were run: first, the clay loosely dumped in place; second, the clay tamped with a 10 lb. hand tamper; and third, the clay tamped in 4 in. layers over the entire backfill area with a petrol-driven (Barco) rammer weighing 210 lb. In the fourth series, the same compaction procedure was employed as in the third but compaction was limited to a zone 18 in. wide adjacent to the wall and the remainder of the backfill was merely dumped loosely in place. The results, Fig. 10, show the average lateral pressures at each level after all compaction was complete. For comparison the at-rest pressure is shown on the same graph.

The results indicate that the residual pressures for the compacted soil greatly exceed those for the same soil loosely placed, and that they are considerably larger than the at-rest pressures. In contrast to cohesionless soils, the compacted pressures do not increase with increasing depth. Observations made of the

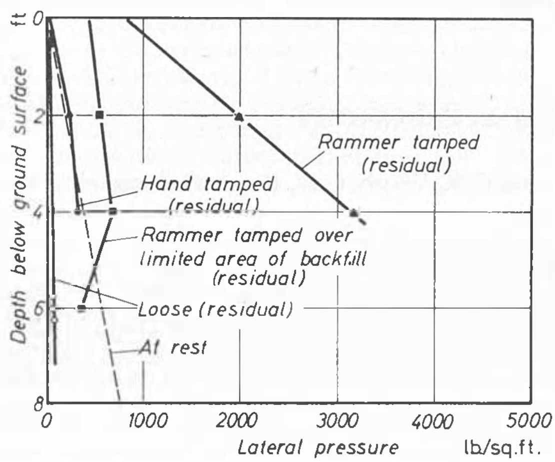


Fig. 10 Residual lateral pressures as functions of depth below the surface of the red sandy silty clay both tamped and loosely placed behind a supported wall at a moisture content of 18 per cent

Les pressions latérales résiduelles en fonction de la profondeur au-dessous de la surface de l'argile rouge qui contient du sable du silt, rendue compacte et placée sans compactage, derrière un mur raide de soutènement à un teneur en eau de 18 pour cent

residual pressures for several days indicate a reduction of about 30 per cent in the first 24 hours but little change thereafter. When compaction was limited to a part of the backfill, the residual pressures were much smaller.

Conclusions

Compaction of backfills may produce lateral soil pressures which exceed those developed by loose backfills of the same soils. This effect is dependent on the deflection of the structure, being greatest when the structure is non-yielding.

The residual lateral pressures in clays increase with increasing compactive effort and decrease with increasing moisture. The residual lateral pressures in cohesionless soils are not greatly influenced by moisture, except insofar as the moisture produces temporary cohesion through capillary tension.

The residual lateral pressures do not appear to change appreciably with time in sands, but drop off slightly in clays during the first day following compaction.

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