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境界 土壓計의 開發

Development of Boundary Pressure Gauge

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要　旨

岩盤에 작용하는 應力을 測定하는데 사용되는 FLATJACK의 原理를 이용하여, 흙을 둘러싼 剛性境界面에 작용하는 鉛直壓力을 測定할 수 있는 壓力計를 開發利用하였다.

本 論文에서는 새로이 制作된 土壓計의 메카니즘, 壓力反應에 대한 보정계수를 얻는 과정 및 模型實驗에 사용한 結果에 대하여 서술하였다. 이 計器를 補強土옹벽의 遠心模型實驗에 장치하여 模型低面의 剛性地盤에 作用하는 鉛直壓力을 측정하였다. 測定結果値와 사다리꼴 鉛直應力分布의 理論値를 비교함으로써 理論의 安當性을 檢證하였다.

Abstract

Based on the mechanism of flatjack used to measure stresses in rocks, a prerssure gauge was developed to measure vertical stresses acting on the rigid boundary in a soil mass. This paper describes the mechanism of the newly built pressure gauge, the process of calibrating the response of this gauge, and its use to centrifugal model tests. By installing this gauge in centrifugal model experiments of reinforced earth retaining walls, vertical stress distribution at the rigid boundary of model wall was obtained and compared with theoretical prediction of trapezoidal vertical stress distribution.

1. INTRODUCTION

Many researchers have designed earth pressure cells and investigated their performances(1,4,6,8). They addressed the difficulty of designing a cell, caused by the nonhomogeneous nature of soil and the cell itself. Nonetheless, some requirements for designing earth pressure cells have been suggested, based on the consideration of factors affecting the performance of the pressure cell : relative size of cell to average grain diameter, size of cell considering stress variation over the acting area of the cell, diameter of cell to central deflection ratio, the ratio of the active area to the total area of the cell face, and relative stiffness between soil and cell material. Most of all, the basic requirement was that the material used for a cell should be stiff enough to minimize the under– or over–registration of applied stresses due to arching action of soil and should be flexible enough to get adequate electrical signal from the cell.

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Most of the earth pressure cells available in the market are of the diaphragm type. They consist of a cylindrical body with chamber closed by a thin diaphragm and a backplate. Various sensing elements have been used to measure the deflection of the diaphragm and these include bonded strain gauges of various types, vibrating wire gauges, piezoelectric crystals and small LVDT displacement transducers.

Being quite different from the pressure cells of diaphragm type, the new pressure gauge was designed in this investigation by adopting the principle of the flatjack for measuring the stress in rocks. The schematic of the pressure gauge is shown in Fig. 1.

As a normal stress is aplied to the soil and subsequently to the face of gauge, the chamber consisting of a membrane and being filled with oil will be compressed. Such a compression of the chamber induces an increase of the oil pressure which is registered by a pore pressure transducer mounted at the bottom of gauge.

For a flatjack, the stress in rock has been measured by applying the hydraulic pressure to the flatjack until the deformation due to cutting the slot for installing the flatkack is recovered to an initial value. On the other hand, for the newly built pressure gauge, the applied pressure to the soil is detected directly by pore pressure transducer via oil pressure built up as a result of compression of membrane. Similar type of pressure cell, measuring oil pressure in the chamber of the pressure cell, was used by other researchers to measure earth pressure in the free field(2,3). However, relatively large size of cell and complicated process of operation made it difficult to be used in such a small model of centrifugal model tests in laboratory. Therefore, a small and simple gauge was required to be used in the laboratory. On the other hand, since the pressure gauge was assembled with a pore pressure transducer, the pore pressure transducer itself could be used for its own purpose of measuring the hydraulic pressure.

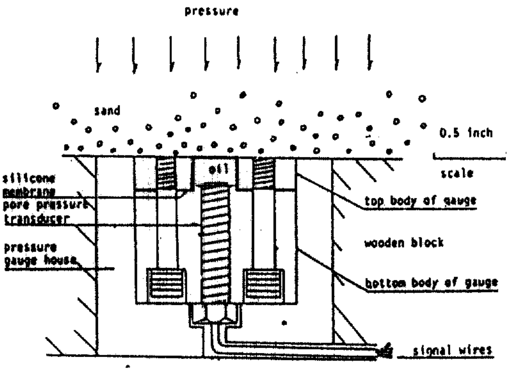

Fig. 1 A schematic of pressure gaug.

2. DESCRIPTION OF PRESSURE GAUGE

As shown in Fig. 2, the pressure gauge consisted of a membrane, two pieces of aluminum body, and a pore pressure transducer. The membrane, forming a chamber where oil was contained, was made of silicone rubber. This silicone rubber membrane was molded from a liquid state of Silastic－HS－RTV manufactured by Dow Corning Corp. This material was often used to construct membranes for the true triaxial testing apparatus by the geotechnical engeneering group in the University of Colorado at Boulder.

The process of making a membrane was as follows. First, Silastic－HS－RTV in the liquid form was mixed with a catalyst accelerating the setting process. This mixture was poured into a mold. A vacuum was applied to remove air entrapped in the mixture, otherwise the entrapped air caused defects in the membrane. The silicone rubber took two days to cure and to gain its full strength. After the mold was removed, the membrane was examined carefully to check whether any defects existed. The process was repeated until a good quality of membrane was made. A miniature pore pressure transducer,

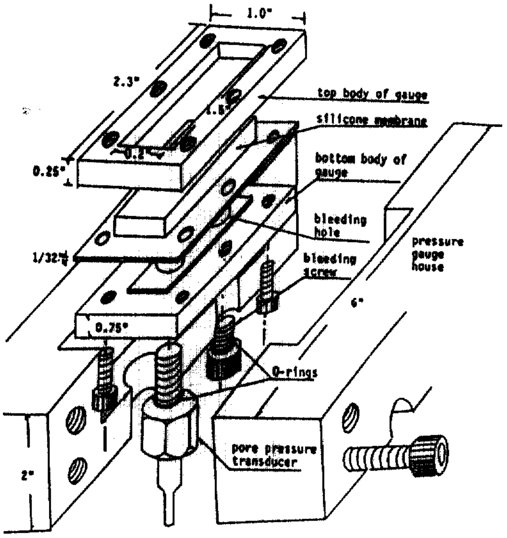

Fig. 2 Overview of presure gauge.

PDCR 200 type manufactured by Druck Inc., was used to measure the oil pressure in the rubber chamber.

The top body of the gauge was used for preventing lateral expansion of the membrane as vertical pressure was applied. The bottom body had two holes : one for a pore pressure transducer and the other for bleeding air. The web of the membrane was placed between two aluminum bodies so that the leakage of oil could be prevented by tightening these bodies and the web of the membrane together with screws. After parts of the pressure gauge were assembled, it was submerged in an oil to fill the membrane chamber with oil. Application of vacuum to the membrane chamber removed the entrapped air in the chamber.

3. CALIBRATION OF PRESSURE GAUGE

The pressure gauge was claibrated by applying surcharge and by using the centrifuge located at the University of Colorado at Boulder.

3.1 Calibration by Surcharge

The pore pressure transducer itself was calibrated first with hydraulic pressure using water before the calibration of the pressure gauge as a whole was performed. After the pressure gauge was assembled, its response to water pressure was investigated. The pressure vs. voltage output is shown in Fig. 3. A perfectly linear response was obtained in both cases.

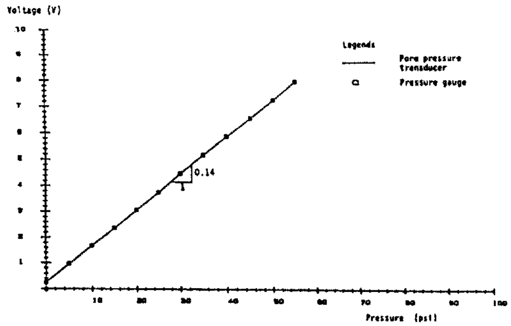

Fig. 3 Calibration of pressure gauge in hydraulic pressure

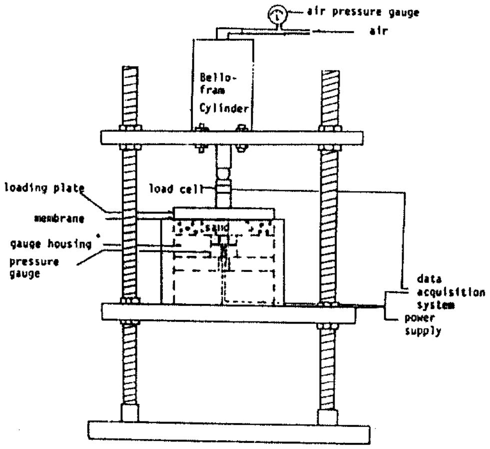

Fig. 4 A schematic of calibration the pressure gauge under surcharges

The schematic of calibrating the pressure gauge by surcharge is shown in Fig. 4. Air pressure was applied to a Bellofram cylinder to transmit a load, via a load cell, the surface of the soil via a loading plate. A rubber membrane was placed between the soil and loading plate to induce a uniform pressure on the surface of the soil.

The soil used for this process was a cohesionless sand called Coyote Concrete Sand from Nevada in the U.S.A. The grain size distribution and properties of this soil are shown in Fig. 5 and Table 1, respectively.

The response of the pressure gauge, obtained from the process of calibrating it by surcharge, is shown in Fig. 6. Values plotted along the x-axis in the figure are loads measured by the load cell. Values plotted along the y-axis are calculated by converting the voltage output, registered by the pore pressure transducer, into values of pressure knowing the calibration from the response of the pressure gauge in water as shown in Fig. 3. A slightly nonlinear response was obtained for stresses below 10 psi while a quite linear response was obtained for higher pressures. The slope of the response was quite parallel to that of the line from calibrations performed in water. During unloading the slope of the gauge response was flatter than that during loading. This might be caused by the irrecoverable strains of the soil element in contact with pressure gauge face.

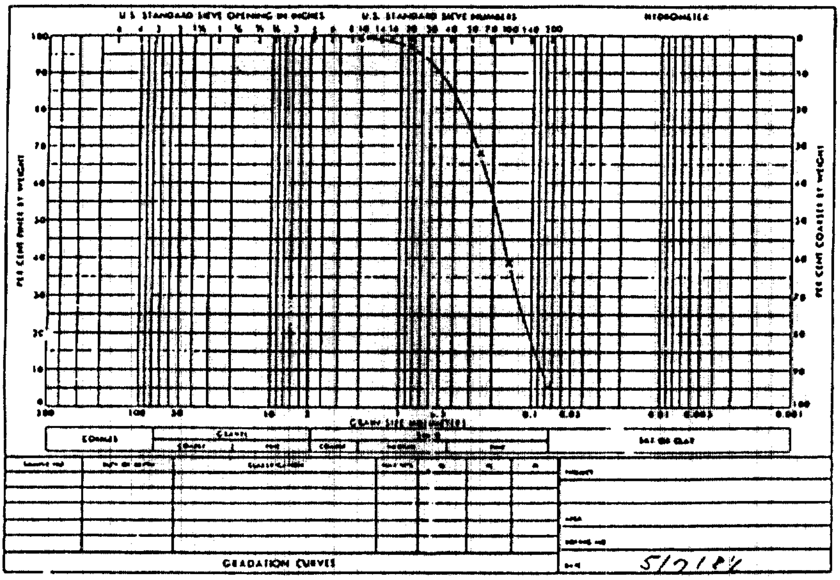

Fig. 5 Grain size distribution

Table 1. Basic soil properties

Maximum dry density	113.3 pcf
Maximum dry density	90.8 pcf
Maximum void ratio	0.89
Maximum void ratio	0.49
Specific Gravity	2.71
Relative density (%)	Internal friction angle (degrees)
70	41.0
80	41.8
90	45.2

Fig. 7. shows scattered responses of the gauge, using different methods of sample preparation and soil densities. Compaction method gave over-registration, whereas vibration vethod resulted in under-registration. This response might be related to the compressibility of soil element adjacent to the face of membrane. The compaction method would result in less stable arrangement of soil particles than the vi-

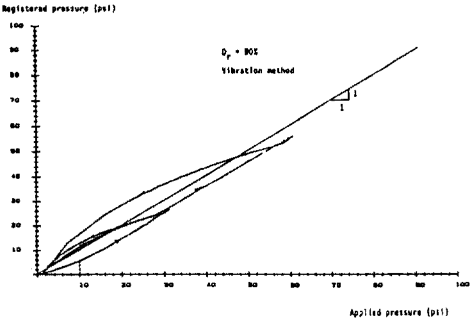

Fig. 6 Calibration result of pressure gauge for the specimen with Dr=90% prepared by vibration Vethod

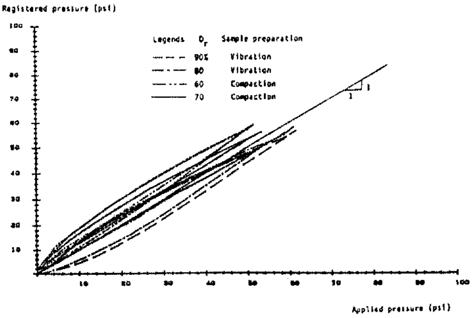

Fig. 7 Calibration results of pressure gauge for specimens with different relative densities and prepatations

bration method. Thus the specimen prepared by the compaction method resulted in greater movement of the membrane than the specimen prepared by the vibration method. Therefore, compaction method might provide over−registration.

For stresses lower than 10 psi, a non−linear response of the pressure gauge might be caused by no perfect contact between the membrane and the side wall of the top body. The gap, if it existed, would be closed as the oil pressure was increased up to a certain threshold pressure. Beyond this threshold pressure, all pressures applied at the face of the membrane would be transmitted to the chamber pressure detected by the transducer without being dissipated.

A tedious process of modifying the gauge was exercised to remove nonlinear response of the gauge and to make a more versatile pressure gauge that would show a consistent response regardless of the soil density and the sample preparation. Several different versions of the gauges are shown in Fig. 8.

An excessive volume of oil was injected into the membrane chamber so that the face of the membrane bulged out slightly, as it is shown in Fig. 8 (a). A strong scotch tape was placed on the face of the membrane. Under such an arrangement, an increase in the oil pressure would cause the sides of the membrane to expand and compress against the side wall of the aluminum body. Therefore, relatively perfect contact between the membrane and the aluminum body could be achieved. This modifiation resulted in a more satisfactory response, i.e., the nonlinearity response at low pressures was diminished as shown in Fig. 9. However, repeated loading cycles caused the tape to be detached from the top face of the aluminum body.

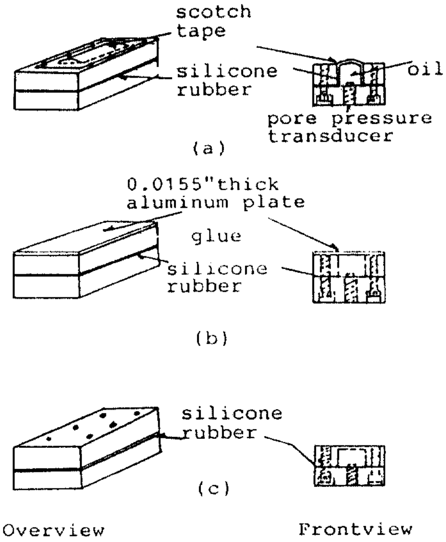

Fig. 8 Different versions of pressure gauges

For the second version of the pressure gauge, a relatively thin aluminum piece of 0.0155 in. in thickness was glued to the top face of aluminum body, as it is shown in Fig. 8 (b). Thus, the problem associated with the first version of the pressure gauge could be removed. But, no glue available in the market was strong enough to withstand shear sstresses developed at the bonded area as the normal stresses acting on the face of the membrane were increased. Test results are shown in Fig. 10. It was noticed that under−registeration of applied pressure was significant. For the second and the third trials more serious under−registerations were obtained. Later, it was found that the thin plate was detached from the top body of gauge. Several different glues were tried to obtain firm bondage between the thin aluminum plate and the top body of the gauge under repeated use. But, no glue worked successfully.

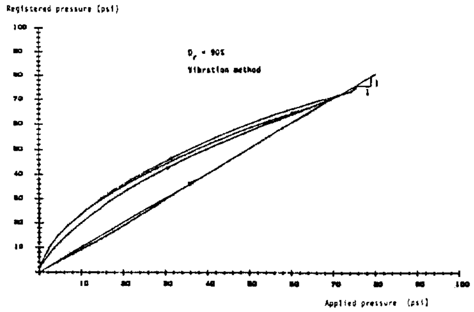

Fig. 9 Calibration results of 1 st version of pressure gauge

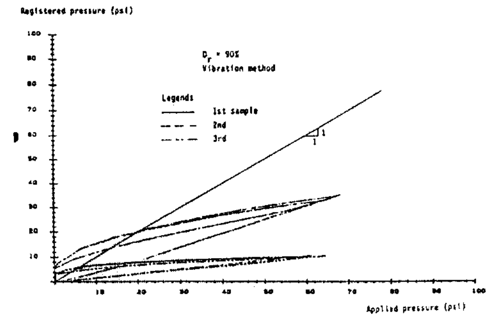

Fig. 10 Calibration results of 2nd version of pressure gauge

Finally, an aluminum body having a thin active face of 0.01 in thickness was made and assembled to the bottom body of the gauge, as it is shown in fig. 8 (c). This version exhibited such a sensitive response to the temperature change that an initial reading could not be stabilized. Consequently, after the several different versions of the pressure gauges were tried, the original version, shown in Fig, 8 (a), was adopted with scceptance of the scattered response.

3.2 Calibration by Centrifuge

The calibration of the pressure gauge was performed by placing the pressure gauge and the soil with various heights in the centrifuge model container and by accelerating the centrifuge.

A schematic of the centrifuge in flight position, located at the University of Colorado at Boulder, is shown in Fig. 11. Two swing baskets were hinged to the ends of rotating centrifuge arms. One of the baskets was used to carry the sample while the other one was utilized as a counterweight mount to balance the centrifuge. The slip ring assembly, mounted on the lid of the enclosure over the main drive shaft, was used to transmit instrumentation signals from the model to the data acquisition system located outside the centrifuge. A closed circuit television video camera (CCTV camera), mounted close to the axis of rotation shaft, was focused on the model so that the behavior of model could be monitored during tests. The image of model was reflected to the CCTV camera

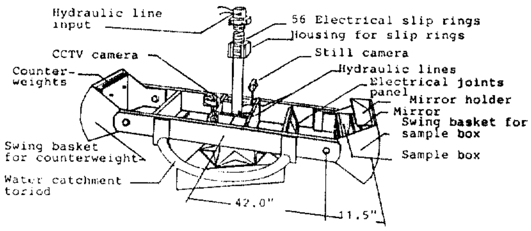

Fig. 11 Schematic of the centrifuge at the University of Colorado at Boulder

through the mirror inclined at 45 degrees to the horizontal direction. The maximum acceleration was usually limited to 100 g corresponding to 273 RPMs. The acceleration of centrifuge was monitored by a digital counter showing RPM's (revolution per minute). Values of RPM were usually converted to gravitational levels (1 g= 9.8 m/s^2).

A pressure gauge and the soil was placed in the model container having inside dimensions of 6 in. by 16 in. by 11.5 in. as shown in Fig. 12. Three sides and the bottom of the model container were constructed of 0.5 in. thick 7075−T6 aluminum. The remaining side was made of 1 in. thick plexiglas so that the behavior of model could be visualized. A pressure gauge was embedded in a block of plywood of 2 in. thick. The excitation voltage of 2 volts D.C. was supplied by a power supply outside the centrifuge through the slip rings. The response signal from the pressure gauge was transmitted to the data acquisition system of IBM pc outside the centrifuge through the slip rings.

The overburden pressure induced by increasing the self−weight of soil, would produce responses from the pressure gauge placed at the bottom of soil. The results are shown in Fig. 13. This process was performed with different heights of soil ; 0 in., 1 in., 2 in., 4 in., 6 in. and 8 in. The same soil as used previously was vibrated to achieve a relative density of 90 % by means of a shaking table. The fairly linear responses were obtained during increase of the g−level whereas serious nonlinear responses were obtained during decrease of the g−level. This behavior was also obtained during calibration by surcharge. A linear response of gauge without any soil, i.e., 0 in. height of soil, was caused by the presence of hydraulic oil pressure in the membrane chamber.

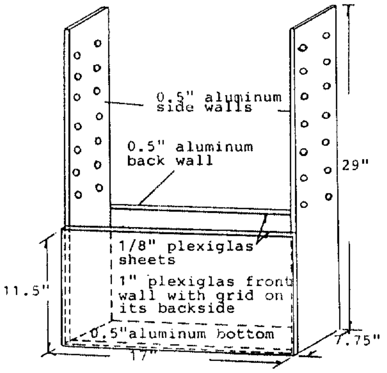

Fig. 12 A schematic of model container

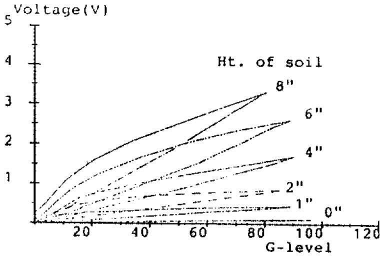

Fig. 13 Calibration results of pressure gauge with centrifuge

When the g−level was converted into the overburden pressure acting on the gauge, the plot of pressure−voltage response was obtained as shown in Fig. 14. Stresses in the x−axis were calculated as $\sigma = N \delta h$ where N is the applied g−leves, δ is the unit weight of soil at 1g, and h is the height of soil. It shows a scatter in response which might have been caused by errors induced during sample preparation and side friction on the wall of container. However, the response can be seen to be fairly linear.

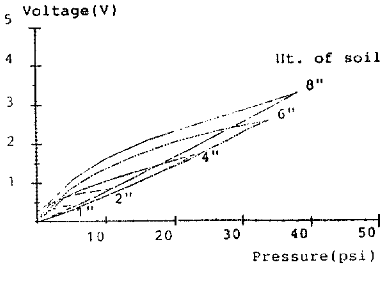

Fig. 14 The plot of registered voltage of pressure gauge with respect to converted pressure

4. THE USE OF PRESSURE GAUGE

A series of pressure distribution tests, one of the testing program for centrifugal model experiments to investigate failure mechanisms of reinforced earth retaining walls due to selfweight of fill and due to strip footing on the surface of wall (6), were carried out to investigate the vertical pressure distribution acting on the base of model wall. Measuring vertical stresses in reinforced earth retaining walls at limit state, the validity of the stress analysis of estimating the maximum tension mobilized in reinforcing strips (5) could be investigated.

A schematic of model wall is shown in Fig. 15. Aluminum strips as a reinforcing material were embedded with regular spacings in backfill. Dimensions of model wall were 9 in. long, 8 in. high and 6 in. wide. Two pressure gauges were embedded in the wooden base of model to measure the vertical stresses acting on the bottom of model wall. Since only two pressure gauges were built, tests were repeated by changing the location of pressure gauge. Thus, an overall profile of pressure distribution on the base of the model wall could be evaluated.

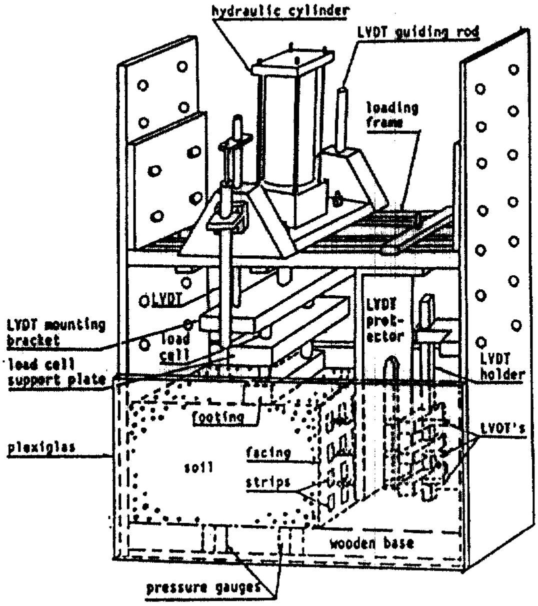

Fig. 15 A schematic of centrifugal model wall and instrumentation

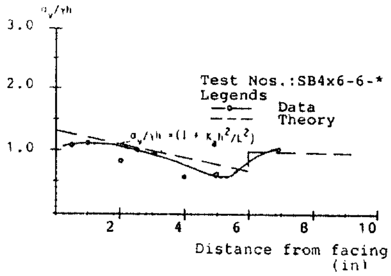

Fig. 16 Measured base pressure with G−level

Fig. 16 shows the variation of vertical pressure with increasing g−level for model walls reinforced by strips with 4 columns by 6 layers arrangement. It represents the response of two pressure gauges located at 1 in. and 3 in. distant from the facing of model wall. Vertical stresses increased non−linearly with the g−level. A nonlinear behavior at low g−level might be caused by the intrinsic property of pressure gauge as discussed previously.

Fig. 17 illustrates the profile of vertical stress distribution at failure for the model wall with 4 by 6 strip arrangement and 6 in. strip length. The measured vertical stress was normalized with respect to the calculated overburden pressure at failure. Test result was compared with theoretical prediction of trapezoidal vertical stress distribution based on the Rankine's stress analysis (6). The measured values had a similar tendency to the predicted values. At the zone close to the facing, the measured value was slightly greater than overburden pressure. How-

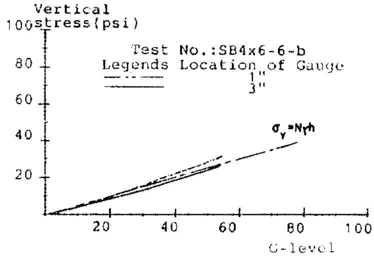

Fig. 17 Base pressure distribution

ever, the measured value was reduced to a lower value than the unity at right behind the facing. This was caused by the friction mobilized on the facing. The reduction of stress was noticeable as the location of pressure gauge was moved away from the facing. The vertical stress was increased to a value of unity at the zone outside the reinforced zone.

By measuring the pressure distribution acting on the base of model wall, it was confirmed that the trapezoidal vertical stress distribution was valid and the reduction of vertical stress near the facing due to the friction mobilized on the facing resulted in increasing the capacity of reinforced earth retaining wall.

5. CONCLUSIONS

Utilizing the mechanism of flatjack used to measure the stress in rock, being controlled by the hydraulic pressure in the flatjack a boundary pressure gauge assembled with a pore pressure transducer was built and used to measure sucessively vertical stresses acting on the base of reinforced earth retaining wall in the centrifugal model experiments. Measurement of stress with this pressure gauge was helped to understand the failure mechanism of reinforced earth retaining wall.

REFERENCES

1. Brown, S. F. (1973). "The Measurement of In-Situ Stresses and Strains in Soils". *British Geotechnical Society Symposium on field Instrumentation*, London, 1973, Field Instrumentation in geotechnical engineering, pp. 38−51.
2. Haws, E.·T., Lippard, D. C., Tabb, R., and Burland, J. B. (1973). "Foundation Instrumentation for the National Westerminster Bank Tower". *British Geotech. Soci. Symp. on Field Instrumentation*, London, 1973, Field Instrument. in Geotech. Eng. pp. 180−193.
3. Irwin, M. J. (1973). "Instruments Developed by the TRRL for studying the Behaviour of Earthworks". *British Geotech. Society Symp. on Field Instrumentation*, London, 1973, Field Instrument, in Geotech. Eng., pp. 194−206.
4. Peattie, K. R. and Sparrow, R. W. (1954). "The fundamental Action of Earth Pressure Cells". *J. Mech. Phys. Soilds.*, Vol. 2, pp. 141−155, Pergamon Press Ltd., London.
5. Schlosser, F. and vidal, H. (1969). "La terre armee". *Bull. de Liais. LRPC*, No. 41 (Nov.), pp. 101−144.
6. Trollope, D. H. and Lee, I. K. (1961). "The Measurement of Soil Pressures". *Proc. 5 th Int. Conf. Soil Mech. Fdns. Engng.*, Vol. 2, pp. 493−499.
7. Yoo, N. J. (1988). "*Centrifugal Model Experiments of Reinforced Earth Retaining Walls*". Ph.d. Thesis University of Colorado at Boulder, Colorado.
8. U. S. Watwerways Experiment Station (1944). "Soil Pressure Cell Investigation."

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