

Pathology of a research error: Coefficient of earth pressure at-rest for cohesionless soils.

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ABSTRACT

The magnitude of lateral earth pressures is required input to geotechnical design and analysis in a wide realm of issues relevant to soil-structure interaction. The determination of lateral earth pressure and its dependence on the over-consolidation ratio (OCR) is often based upon the coefficient of earth pressure at-rest, (K_0), for which no rational method of determination is available.

This paper addresses three issues:

- i) What is the quality of the data which was the basis for the formulations often noted in the literature, taught in our classrooms and referenced in national standards and guidelines?
- ii) What is the outcome when rigorous testing, accounting for issues which have usually negatively affected the determination of K_0 , is carried out? These issues include: Pressure measurement technique, Boundary conditions and Stress history.
- iii) To what other areas/scenarios have these erroneous measurements and resulting faulty concepts of K_0 been propagated, and how does this affect engineering and research decision making?

The testing procedures implemented to produce the data used to develop commonly applied relationships for K_0 do not meet the basic requirements of at-rest conditions.

The small deflections required to produce output signals corrupt the actual measurement. Boundary conditions of the test set-up must be considered when determining K_0 . The boundary conditions affect the vertical soil pressure, and as a result the development of lateral soil pressure. Formulations often used in estimation of K_0 in cases of unloading do not properly emulate the response of granular soils.

The concept that the OCR has overwhelming influence on the development of horizontal soil pressure has been used in the past to develop models which attempt to determine/estimate the development of horizontal soil pressure due to compaction and may, consequently, result in significant over-estimation of residual pressure due to soil compaction activities. Is this approach a correct one ?

RESUME

La magnitude des pressions terrestres latérales est un élément essentiel de la conception et de l'analyse géotechniques dans un large éventail de questions relatives à l'interaction sol-structure. La détermination de la pression terrestre latérale et de sa dépendance au taux de surconsolidation (OCR) est souvent basée sur le coefficient de pression terrestre au repos (K_0), pour lequel aucune méthode de détermination rationnelle n'est disponible.

Cet article aborde trois questions:

- i) Quelle est la qualité des données sur lesquelles reposent les formulations souvent mentionnées dans la littérature, enseignées dans nos salles de classe et référencées dans les normes et directives nationales?
- ii) Quel est le résultat lorsque des tests rigoureux, prenant en compte des problèmes qui ont généralement eu un impact négatif sur la détermination de K_0 , sont effectués? Ces problèmes incluent: la technique de mesure de la pression, les conditions aux limites et l'historique du stress.
- iii) Dans quels autres domaines / scénarios ces mesures erronées et les concepts faussés de K_0 qui en résultent ont-ils été propagés, et comment cela affecte-t-il la prise de décision en matière d'ingénierie et de recherche?

Les procédures de test mises en œuvre pour produire les données utilisées pour développer les relations couramment appliquées à K_0 ne répondent pas aux exigences de base des conditions de repos.

Les petites déviations nécessaires pour produire des signaux de sortie altèrent la mesure réelle. Les conditions de limite des configurations de test/d'essai doivent être prises en compte lors de la détermination de K_0 . Les conditions de limite affectent la pression verticale du sol et, par conséquent, le développement de la pression latérale du sol. Les formulations souvent utilisées dans l'estimation de K_0 en cas de déchargement ne reproduisent pas correctement la réponse des sols granulaires.

Le concept selon lequel l'OCR a une influence prépondérante sur le développement de la pression horizontale du sol a déjà été utilisé par le passé pour développer des modèles cherchant à déterminer / estimer l'évolution de la pression horizontale du sol due au compactage et pouvant, par conséquent, entraîner une surestimation importante de pression résiduelle due aux activités de compactage du sol. Cette approche est-elle correcte?

1 PROLOGUE

The development of scientific theories and engineering concepts are often based upon measurements and observations. Theories and concepts developed upon such observations, and later concepts that are based upon those earlier concepts, are only as good as the original data. This is even more evident when no physical/analytical frameworks are available to verify the correctness of measurements past and present. As a result, concepts and procedures that we use may be flawed, not as a result of mathematics, but rather because of the data on which they were founded. Over time and experience our understandings and abilities to comprehend the reliability of measurements should be reviewed. The quality of the original data should be reconsidered, and an attempt made to investigate how inappropriate conclusions might have propagated and mutated into our understandings and design considerations.

The problem is that this process requires that we, as a profession and as a field of study, be capable of saying: maybe we made a mistake. If we are not capable of going through this process, we are in fact creating a barricade to the development of our profession. This happens when new, rigorous and different observations do not find a place in the professional literature and are rejected because they do not fit with the “accepted” models. Not because the new data is wrong; rather because the original model may have been based on faulty data. It is time to allow new and basic ideas to gain exposure.

2 THE ISSUE

The magnitude and distribution of horizontal soil pressure at at-rest conditions is often an important piece of information in geotechnical analysis and design. Unfortunately, determination of the magnitude of horizontal earth pressure (σ'_h) at-rest and the coefficient of earth pressure at-rest (K_o) both fall into that set of problems for which there is no correct, closed form solution. In 1948 Jaky presented a theoretical relationship for the determination of K_o , written in its simplified form shown here as Equation [1].

$$K_{o\ N/C} = \frac{\sigma'_h}{\sigma'_z} = 1 - \sin\phi' \quad [1]$$

where:

$K_{o\ N/C}$ corresponds to soils in the normally consolidated condition, σ'_z represents the effective vertical pressure at the point of consideration of σ'_h , and ϕ' represents the effective angle of internal friction.

Equation [1] may be a theoretical development, however, it is also theoretically incorrect. The fact that Equation [1] includes the angle of internal friction (ϕ') results from Jaky's assumption of a plastic condition of limiting shear equilibrium, which is not the case for K_o conditions. This flaw may be considered the original error. It paved the way for other researchers to rely on this error and to perpetuate it.

Schmidt (1966) suggested that Equation [1] could be extended to consider unloading, such that K_o for soils in the over-consolidated condition could be determined according to Equation [2]. Mayne and Kulhawy (1982) suggested that the exponent α could be statistically equated to $\sin\phi'$ (Equation [3]). In the same study Mayne and Kulhawy presented an empirical relationship (Equation [4]) as a method to estimate K_o for cases when soil undergoes virgin loading, unloading and subsequent reloading. On the face of it, the equation is very compact and elegant; all that is needed, in addition to knowledge of the stress history, is to guess/choose a value for the angle of effective internal friction (ϕ') and presto, we have K_o .

$$K_{o\ O/C} = \frac{\sigma'_h}{\sigma'_z} = K_{o\ N/C} \cdot OCR^\alpha \quad [2]$$

$$K_{o\ O/C} = \frac{\sigma'_h}{\sigma'_z} = K_{o\ N/C} \cdot OCR^{\sin\phi'} \quad [3]$$

$$K_o = \frac{\sigma'_h}{\sigma'_z} = (1 - \sin\phi') \cdot \left[\frac{OCR}{OCR_{max}^{1-\sin\phi'}} + \frac{3}{4} \cdot \left(1 - \frac{OCR}{OCR_{max}} \right) \right] \quad [4]$$

Where OCR is the over-consolidation ratio and OCR_{max} represents its maximum value at any point during a load-unload-reload cycle.

Equations [2] and [3] have found their way into national standards (Israel Standards Institute, 2008), design codes (FHWA 2006) and engineering handbooks (Canadian Geotechnical Society 2006). These equations, and their concepts, are regularly taught in university classrooms. Equation [3] also formed the basis for other theories and concepts used in engineering design. For example, it forms the basis for the increment of horizontal soil pressures which remain “locked in” within a soil mass or next to a non-translating retaining structure as a result of compaction activities at the ground surface (Duncan and Seed 1986, Duncan et al. 1990).

It is therefore desirable to re-consider the empirical basis on which Equations [1 and 3] were founded/accepted.

3 EMPIRICAL BASIS

Equations [1] [3] and [4] were developed or verified from statistical evaluation of many data sets which Mayne and Kulhawy found in the literature or obtained from co-workers; in total, 171 data sets, 89 of which were from testing performed on cohesionless materials. These data sets were produced by many researchers, through testing of both cohesionless and cohesive materials, using broadly five different laboratory arrangements: Flexible Ring Oedometers, Rigid Ring Oedometers, Null Consolidometers, Triaxial Testing and soil pressure transducer testing in pressure vessels. Mayne and Kulhawy considered cohesive and non-cohesive materials separately, however they suggested that Equations [1], [3] and [4] were representative for both. The question is: how much, and which of the data, are sufficiently credible in order to develop a useful and reliable relationship between K_o and the over consolidation ratio.

The definition and constraints of the K_o condition are such that its determination requires the ability to define:

- a representative value for σ'_h
 - a representative, corresponding value for σ'_z both under conditions of zero lateral strain.
- Zero is a very small number, and a difficult one to work with. How much movement is allowable before a measured value is no longer representative? Talesnick (2014) showed that even minute deflections significantly corrupt the measurements.

Without exception, the different methods used by the different researchers, each in its own way, do not meet one, or both, of the requirements noted above. Flexible ring oedometers, as used, for example, by Belloitti et al. (1976), require deflection in order to produce a response during loading. As a result, they may display under-registration during loading and induce significant over-registration during unloading. The same is true for rigid ring oedometers (e.g. Belloitti et al. 1976, Sheriff et al. 1974), where deflecting membrane sensors or load cells are used to measure lateral soil pressure. In these cases, the sensors themselves are compliant and they induce a response similar to that seen when using flexible ring oedometers. Null consolidometers (e.g. Hendron 1963, Brooker and Ireland 1965), if properly designed, could be appropriate, however they suffer from a different issue, that of sidewall friction. Sidewall friction affects the ability to define a representative value for σ'_z (e.g. Sivrikaya and Togrol 2006, Lodahl et al. 2016, Nachum 2018). During the loading segment of a consolidation test, sidewall friction will, in all cases, cause the representative vertical pressure to be smaller than that applied to the specimen top. During unloading, sidewall friction will cause the representative vertical stress throughout the specimen to be larger than that applied to the specimen top. If the applied vertical pressure is chosen to be a representative value for σ'_z , the K_o value determined during loading will be underestimated, while in subsequent unloading it will be overestimated. Sidewall friction induces hysteresis in vertical pressure during unloading, which in turn induces parasitic hysteresis in horizontal pressure during unloading. This issue is equally true for flexible and rigid ring oedometers. The oedometer data used by Mayne and Kulhawy did not account for, or even address this issue. Its importance will be illustrated in a later section of the paper.

When using triaxial testing, the shape of the specimen changes during loading and unloading as a result of end friction. This condition causes barreling or thinning of the specimen at its center making reliable feedback on diametric changes unreliable. There has been some success in using triaxial data (Bishop 1958, Santana and Candeias 2015). In both cases these data illustrate much smaller hysteresis than suggested by Equation [3].

Use of soil pressure transducers embedded in the soil tested in pressure vessels is another test set up that was used by researchers from whom Mayne and Kulhawy gathered data. The issue of side wall friction may be dealt with by adopting a generous width to height ratio of the testing vessel and in taking steps to reduce friction along the sidewalls (Tognon et al. 1999). In order to obtain sound

data from this setup, the method of measuring soil pressure must be rigorous. If deflecting membrane transducers are used, the measurements are corrupted, as discussed above.

Of the 89 data sets collected by Mayne and Kulhawy for cohesionless soils, 63 included load-unload segments. 30 out of 63 were attributed to Sheriff et al. (1974), which was sourced from an MSc thesis by Ryden (1974). Of the remaining 33 data sets, 22 were attributed to Al-Hussani and Townsend (1982). These were performed using triaxial testing systems and therefore suffered from the complications discussed above.

Equations [3] and [4] include Equation [1], which considers the normally consolidated case. There is no theoretical foundation to Equation [1], the original sin. This error has been propagated and “verified” by experimental work that does not faithfully uphold K_o conditions or faithfully define representative vertical pressures, nor rigorous measurement of horizontal pressure. There is no credence in verifying a flawed equation with data from flawed experiments. Basing K_o on a value of ϕ' is not only theoretically incorrect, it is also unclear which representation of ϕ' to use, in which testing device to determine ϕ' or in what conditions plane strain or axis symmetry should be determined. The authors do not agree with the foundation of Equation [1], however will use it below in order to consider the credence of Equation [3].

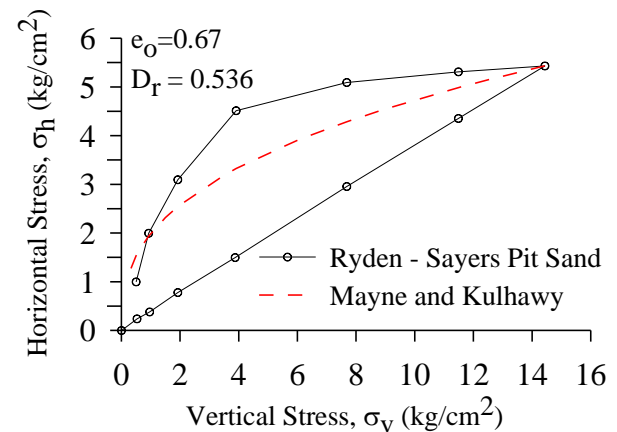


Figure 1. Development of horizontal soil stress as a function of applied vertical pressure (Ryden 1974).

Ryden's tests were performed on semi-circular cylindrical samples 89 mm high, by mechanically returning a confining plate on the sample diameter after development of a displacement of 0.0002" (5.5 μ m). The fact that the soil deforms and is then forced to return is an important deviation from at rest conditions. Zero is a small number. The effects of sidewall friction were not taken into account. An example data set from Ryden (1974, Figure 4.27) is shown in Figure 1. The plot illustrates extreme hysteresis. Based on the form of Equation [1] and the slope of the initial loading curve, a value of $\phi' \sim 36^\circ$ is determined. The expected rebound curve according to Mayne and Kulhawy, using Equation [3], was determined and is shown in the plot. The curve is far from being a good representation of

Ryden's data. All of the plots presented by Ryden are of the same form. In fact, 20 of the 30 α values listed by Mayne and Kulhawy were above 0.65, corresponding to a ϕ' of 41°, a relatively high value considering that the relative densities of 21 of the 30 tests were below 70%.

Among the data used by Mayne and Kulhawy, is the plot of Figure 2a, taken from the MSc thesis of Weiler (1979, Figure 5.28). Figure 2b is from Mayne and Kulhawy (1982). Clearly the plot of Figure 2b was taken directly from Weiler (1979); ϕ' was found from the best fit loading segment and used with equation [3] to draw the rebound curve which was found to fit through the experimental points. Of the 171 pieces of data that Mayne and Kulhawy used in their paper, the data of Figure 2b is the only/singular plot chosen to directly compare to the relationship of Equation [3].

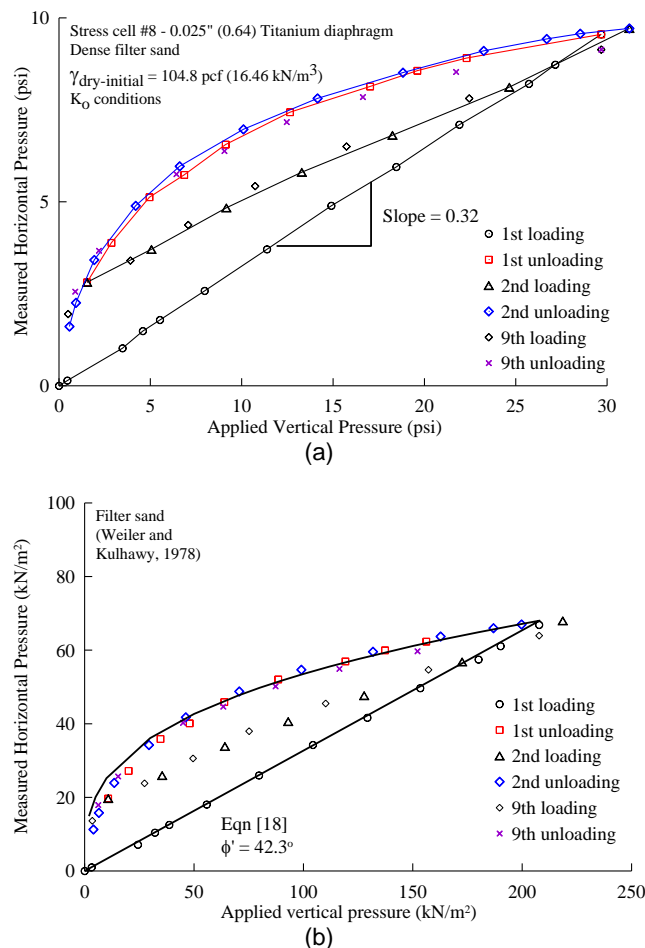


Figure 2. Development of horizontal soil pressure as a function of applied vertical pressure; (a) after Weiler (1979) (b) after Mayne and Kulhawy (1982).

Since Weiler's data has been given seminal significance and at the same time provides an excellent representation of Equation [3] it is relevant to consider how that data was generated. Weiler's tests were performed by placing a deflecting membrane soil stress cell (in a vertical orientation to measure horizontal soil pressure) in the soil

in a pressure vessel and applying uniform vertical pressure on the soil surface. Under these conditions the sensor responded to at-rest horizontal soil pressure. In order to interpret the output of the stress cell, calibration tests were performed by orienting the same soil pressure cell horizontally in the soil pressure vessel so that it reacted directly to the applied vertical pressure. Figure 3 (Figure C2.12 from Weiler 1979) presents the calibration of the sensor (#8-0.025" Titanium Diaphragm) that was used to generate the data of Figure 2 as tested in the same dense filter sand. The calibration shows a linear relationship during loading, but the response to unloading is both non-linear and hysteretic. The hysteresis is an erroneous, inherent result of soil-structure interaction which develops due to parasitic membrane deflection (Talesnick 2005, 2013 and Talesnick et al. 2014). Weiler made no mention in the thesis of how the issue of hysteresis in the calibration was handled in order to determine soil pressures in unloading. Rather, he attempted to explain why this hysteresis is acceptable. It can only be assumed that the same calibration factor obtained for loading was used for unloading. It is important to understand that by using the same calibration factor for loading and unloading Weiler erroneously included the inherent hysteretic response of the soil-sensor interaction into the response, he interpreted, of the soil.

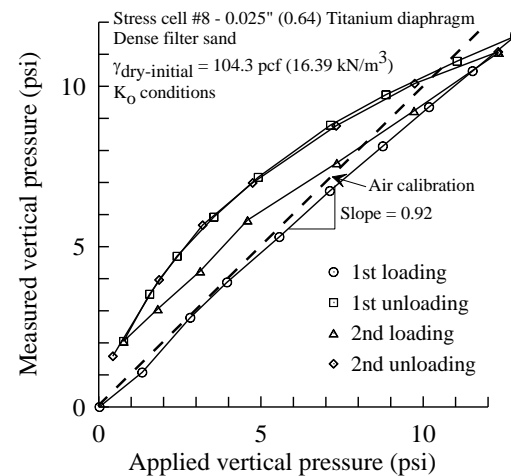


Figure 3. Calibration of Stress cell #8, (Weiler 1979).

In 1983 a PhD thesis was submitted by Dr. Steven Craig Boyce to Cornell University under the supervision of Prof. F. Kulhawy. The thesis was very thorough and very well done. To the authors' knowledge, no publication was ever made from the material of this thesis. Of the very interesting material of the thesis was an entire chapter dealing with unwanted hysteresis, time effects and issues concerning the calibration of the Cornell Stress Sensor as used by Weiler. Boyce submitted his thesis in 1983, nothing from his thesis was ever published. Mayne and Kulhawy not only published data from Weiler's thesis but used a single example to validate Equation [3].

From the mass of data used by Mayne and Kulhawy to consider the development of horizontal pressures of

cohesionless soils under K_0 conditions, little to none of the methods meet the testing requirements needed to faithfully estimate values for K_0 .

4 A MORE RIGOROUS TACT AND A DIFFERENT RESULT

Recent studies have illustrated the importance of:

- completely eliminating membrane deflection in the measurement of soil pressure.
- eliminating or measuring and accounting for side wall friction in oedometer testing.

These two procedures are obligatory in order to obtain representative values of soil pressure required to faithfully determine K_0 . Rigorous methods are available to deal with these issues, and their use leads to results different from those used to develop Equations [3] and [4]. It is time to realize that previous experimental misinterpretations have led to conceptual errors and have lodged them into the body of knowledge.

Monroy et al. (2014) presented results from a well designed, reliable null consolidometer. Their results are interesting and most likely correct. Despite this, they seemed almost apologetic that their results were different from current expectations.

Talesnick (2005, 2013) and Talesnick et al. (2014) described the null approach to the measurement of soil pressure. This rigorous approach involves actively pre-empting and preventing sensor deflection. By applying this approach, the issues of soil structure interaction and soil arching seen during calibration (like those seen in Weiler's data) are effectively eliminated. Figure 4 illustrates this outcome for a uniformly graded, coarse grained quartz sand (SP, $D_{50}=1.5\text{mm}$), placed in both dense and loose conditions. The calibration curves are unique, independent of material or stiffness, and are linear and free of hysteresis during unloading.

Nachum (2018) performed tests on rectangular sand specimens in which the vertical pressure reaching the specimen bottom was monitored as a function of the pressure applied to the specimen top. Horizontal pressure was measured at sample mid-height using null gauges, on two opposite specimen sides. Throughout the loading and unloading cycle (Figure 5) it is obvious that hysteresis develops in the vertical pressure reaching the specimen bottom, and as such also at the mid-height of the specimen, the point at which horizontal pressures were measured. The outcome of this process is the understanding that at least part of the hysteresis subsequently measured in the horizontal pressure during unloading is actually due to hysteresis in vertical pressure which develops as a result of the testing methodology, and has nothing to do with soil behavior. In order to counter this outcome, the gradient of vertical soil pressure must be accounted for either by eliminating side wall friction or by defining a reasonably representative value for the actual vertical pressure through measurement.

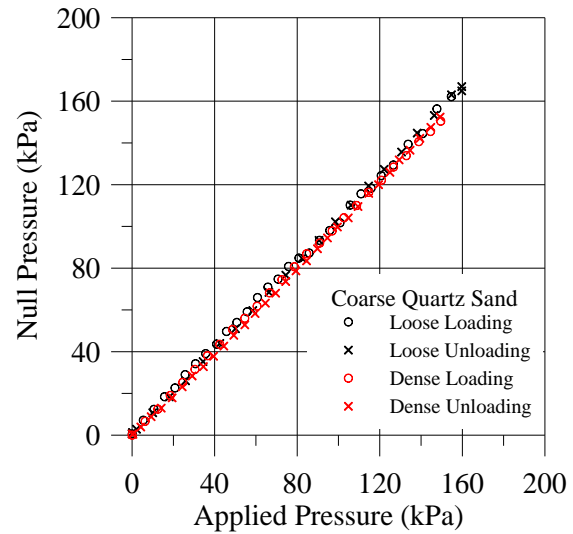


Figure 4. Verification of soil pressure sensor using the Null System. (Talesnick et al. 2014)

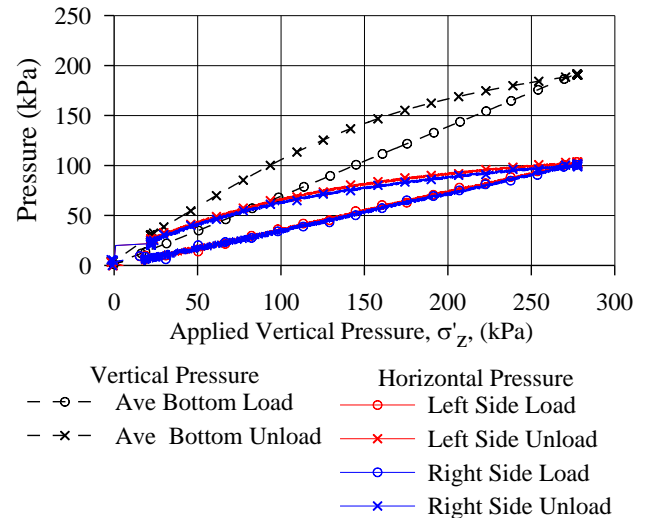


Figure 5. Effect of sidewall friction on vertical pressure (after Nachum 2018).

When eliminating issues of sidewall friction and issues of membrane deflection, it is found that the development of horizontal soil pressure, as a function of a load unload cycle of vertical pressure under K_0 conditions, is far flatter than that described by Equation [3]. This is illustrated in Figure 6 for an experiment performed on the same sand as considered in Figure 4 (based on data from Talesnick 2102). If the form of Equation [2] is accepted, the exponent, α , that best fits the data, is 0.16, far smaller than any value that would be considered reasonable for $\sin\phi'$. The fit is very good, far more appropriate than that of Equation [3] and illustrates the importance of eliminating membrane deflection and accounting for sidewall friction in the measurement of soil pressure.

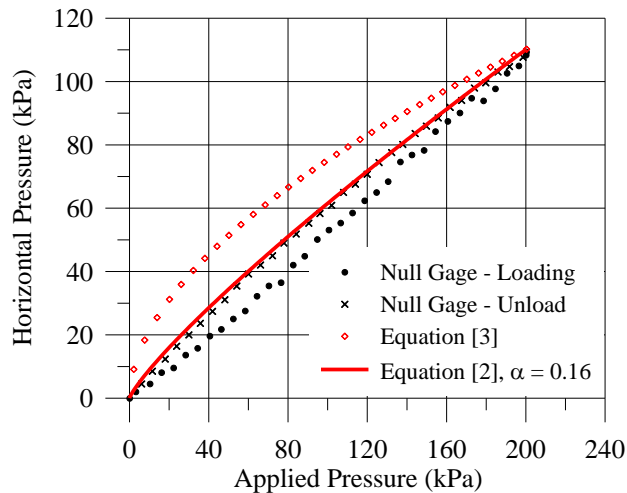


Figure 6. Development of horizontal soil pressure in a coarse quartz sand (after Talesnick 2012).

5 EPILOGUE

Unfortunately, many researchers continue to use some of the same older approaches, despite and even though at times they know that they are incorrect. This creates a form of a negative reinforcement feedback loop. They present results based on flawed procedures, which match previous conclusions drawn through flawed procedures. For example, Lee et al. (2013) presented a very interesting study aimed at considering the effects of particle shape and intrinsic frictional properties of sand on the development of K_0 as a function of stress history. They based their study on testing of a set of materials using a flexible ring oedometer, while assuming sidewall friction to negligible. The issue here is twofold:

- The importance of particle shape and intrinsic particle friction may have been masked by the parasitic effects of cell wall friction and flexible ring deformation, and as a result new and important experimental data may have been lost.
- The next time that a researcher submits research done through due diligence, and deals with these issues more rigorously, he/she will present results which differ from Lee et al. (2013), and those of previous erroneous studies.

In either eventuality, new and possibly important data, based on more rigorous procedures may not be published, and the cycle continues. Should the data shown in Figure 6 see the light of day, or should we hide it because it does not fit what we once thought to be correct?

A troubling outcome of the pathology outlined above is the propagation of errors into other fields of geotechnical practice and research. In geotechnical engineering the effect of compaction activities on the development of horizontal stress and residual horizontal pressure is a topic of both practical and research interest. There is no doubt that compaction activities do induce horizontal pressures both within a soil mass, and on a non-translating retaining

structure either within a soil mass, or at a boundary with a soil mass. However, do significant residual horizontal pressures remain acting on the that boundary after completion of the compaction activities? Duncan and Seed (1986) and Duncan et al. (1991) based their determination of locked in soil compaction pressures on the concepts put forth by Mayne and Kulhawy (1982). As has already been shown, the data on which Mayne and Kulhawy based their correlation is questionable and so the research error is propagated.

6 REFERENCES

- Al-Hussani, M.M. and Townsend, F.C., (1975) Investigation of K_0 Testing in Cohesionless Soils: Technical Report S-75-16, Waterways experiment Station, Vicksburg, Miss.
- Bellotti, R., Formigoni, G., and Jamiolkowski, M. B., (1975), Remarks on the Effect of Overconsolidation on the Coefficient of Earth Pressure at Rest, Istanbul Conference on Soil Mechanics and Foundation Engineering, pp. 17–25.
- Bishop, A.W., (1958), Test requirements for measuring the coefficient of earth pressure at rest. Conference on Earth Pressure Problems, Brussels, pp. 2-14.
- Brooker, E.N. and Ireland, H.O., (1965), Earth pressures at rest related to stress history. Canadian Geotechnical Journal, 11(1), 1-15.
- Boyce, C.S. (1983), Laboratory determination of horizontal stress in cohesionless soil. PhD Thesis presented to the Faculty of the Graduate School of Cornell University.
- Canadian Geotechnical Society, (2006), Canadian Foundation Engineering Manual, 4th edition.
- Duncan, J.M. and Seed, R.B., (1986), Compaction induced earth pressure under K_0 conditions. ASCE, Journal of Geotechnical Engineering, Vol. 112, No. 1.
- Duncan, J.M., Williams, G.W., Sehn, A.L. and Seed, R.B., (1991), Estimation earth pressures due to compaction. ASCE, Journal of Geotechnical Engineering, Vol. 117, No. 12, pp. 1833-1847.
- FHWA Federal Highway Administration (2006), Soils and Foundations, Reference Manual. National Highway Institute, FHWA-NHI-06-089.
- Hendron, A.J., (1963), The behavior of sand in one-dimensional compression. PhD thesis, Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urban, IL.
- Israel Standards Institute, (2008), Israel Standard 940, Part 1: Geotechnical design: Geotechnics and foundations for civil engineering.
- Jaky, J. (1944), The coefficient of earth pressure at rest. J. society of Hungarian Architects and Engineers, 355-358. (In Hungarian).
- Lodahl, MR, Sørensen, K.K., Mortensen, N. and Trankjær, H., (2016), Oedometer tests with measurement of internal friction between oedometer ring and clay specimen. Proceedings of the 17th Nordic Geotechnical Meeting: NGM 2016 - Challenges in Nordic Geotechnics. The Icelandic Geotechnical Society, Reykjavik, Iceland, 289-298.

- Lee, J., Yun, T.S., Lee, D. and Lee, J., (2013), Assessment of K_0 correlation to strength for granular materials. *Soil and Foundations*, The Japanese Geotechnical Society, 53(4), 584-595.
- Mayne, P.W. and Kulhawy, F.H., (1982), K_0 -OCR relationships in soil. *ASCE Journal of the Geotechnical Division*, 108(GT6), 851-872.
- Monroy, R., Zdravkovic, L. and Ridley, A.M., (2013), Evaluation of an active system to measure lateral stresses in unsaturated soils. *Geotechnical Testing Journal*, 37(1), 71-84.
- Nachum, S., (2018), The relationship between three dimensional stresses and strains during one dimensional loading, unloading and swelling of unsaturated clay. MSc. Thesis, Technion-Israel Institute of Technology (In Hebrew).
- Ryden, D.E., (1974), An experimental investigation of the coefficient of lateral earth pressure at rest in cohesionless soils. MSc. Thesis, University of Washington.
- Santana, T. and Candeias, M., (2015), K_0 Measurement in a Sand Using Back Volume Change, *Soils and Rocks*, São Paulo, 38(1): 3-8, January - April.
- Schmidt, B., (1966), Lateral stresses in uniaxial strain. *Geoteknisk Institut, The Danish Geotechnical Institute, Bulletin No. 23*, pp. 5-11.
- Sheriff, M.A., Ishibashi, I. and Ryden, D.E., (1974), Coefficient of lateral earth pressure at rest in cohesionless soils. Soil engineering research report No. 10, University of Washington, Seattle.
- Sivrikaya, O., and Togrol, E., (2005), Measurement of side friction between specimen and consolidation ring with newly designed oedometer cell. *Geotechnical Testing Journal*, 29(1), 87- 94.
- Talesnick, M., (2005), Measuring soil contact pressure on a solid boundary and quantifying soil arching. *Geotechnical Testing Journal, ASTM*, 28(2), 171-179.
- Talesnick, M., (2012), A different approach and result to the measurement of K_0 of granular soils. *ICE, Geotechnique*. 62(11), 1041 –1045.
- Talesnick, M., Ringel, M. and Avraham, R., (2014), Measurement of contact soil pressure in physical modeling of soil-structure interaction. *ICE, International Journal for Physical Modeling in Geotechnics*, 14(1), 3-12.
- Tognon, A.R., Rowe, R.K., Brachman, R.W.I. (1999). Evaluation of side wall friction for a buried pipe testing facility. *Geotextiles and Geomembranes*. 17(4),193–212.
- Weiler, W.A. (1979), An investigation of the behavior of stress cells in soil. MSc Thesis, Cornell University, NY.