A Consideration of Compaction Pressures for Retaining Wall Design in a New Zealand Context

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ABSTRACT

The permanent works design of retaining walls in New Zealand typically focusses on the assessment of seismic loading and its impact on the structure. This is also reflected in the emphasis of New Zealand design guidance on seismic engineering considerations for earth pressure loading of retaining walls. In contrast, there can often be an absence of detailed commentary on non-seismic aspects. Compaction pressures are one such phenomena that may dominate non-seismic loading. However, in the authors' experience, the underlying theory is often inconsistently applied by practitioners in New Zealand.

A literature review has been carried out, reviewing the theoretical derivation of compaction-induced lateral earth pressures on retaining walls. A summary is presented on the recommendations given by design standards and guidelines, and the application of these recommendation to typical construction in New Zealand. An opportunity for improved commentary from New Zealand specific guidance is identified and recommended.

Keywords: Retaining Walls, Compaction Pressure, Lateral Earth Pressures

1 INTRODUCTION

Retaining walls are most easily classified as 'gravity', 'cantilever' and 'anchored' systems. Gravity systems typically involve rigid or stiff, inflexible elements, where the predominant direction of movement of the structure in yielding to soil pressure is translational (sliding). Cantilever systems often involve flexible wall elements, where the predominant direction of movement of the structure is rotational. The design of anchored systems is somewhat different and is not the focus of this paper.

Static earth pressures acting on retaining walls are primarily a function of the movement of the structure relative to the adjacent soil. Three primary states of static earth pressures are defined: active (relating to movement of the wall away from the soil), at-rest (no movement), and passive, (movement towards the soil). Where the wall is designed for no movement, it is described as 'rigid'. In contrast, if it is designed to permit deflections greater than ~0.5% of the retained height of the wall, it is described as 'flexible'. 'Stiff' walls are those designed for an intermediate degree of movement, typically in the order of 0.2% of the retained height of the wall (Wood and Elms, 1990).

Several classical theories were developed to determine the limiting values of the active and passive states. Coulomb (1776), Rankine (1857), and Caquot et al. (1948) are well-known examples. Defining these limiting active and passive pressure distributions is significant as, in either case, further movement would result in shear failure of the soil. In a limit equilibrium design, they are therefore intended to describe the maximum earth pressures that the wall could be expected to experience. The at-rest state differs meanwhile in that is does not have a limiting value; rather, it is an estimation of the pressure distribution when there is no relative movement between the soil and wall.

Since the 1930's testing has been undertaken on retaining walls with compacted backfill incorporated into their construction. These tests have consistently found that the measured lateral earth pressures can significantly exceed the limiting values of the classical theories (Coyle and Bartoskewitz, 1967; Ingold, 1979a; Duncan and Seed, 1986). These higher pressures remain until greater outward deflection of the wall occurs (Coyle and Bartoskewitz, 1967). Cohesive backfill has also been identified to present time dependent pressure distributions (Heidra-Cobo, 1986; Symons and Clayton, 1992).

Where that outward deflection is constrained, such as in the design for rigid or stiff walls, then the pressures to be resisted by the internal structure of the wall are higher than would otherwise be calculated from classical theory. For flexible walls, where such outwards deflection isn't constrained, the magnitude of that deflection would instead be greater than otherwise anticipated. As such, careful consideration of the effects of compaction is warranted in retaining wall design.

2 COMPACTION EARTH PRESSURE THEORY

2.1 General

Compaction-induced earth pressure theory has developed as a means of describing the discrepancy between measured lateral pressure distribution and classical theory for retaining walls with compacted backfill. It has largely focused on the concept of such compaction being analogous to an over-consolidation of the backfill material. It is premised on the concept that the increased lateral stresses, developed from the compaction plant, remain elevated, in at least some proportion, after the compaction plant is removed. The theories are typically presented as a substitute to the classical pressure distributions, rather than as an excess pressure to be superimposed. A selection is discussed below.

2.1 Rowe (1954)

Rowe developed a modified at-rest earth pressure coefficient to be considered in the calculation of earth pressures acting on a rigid wall. This was based on experimental testing using a bi-directional shear box using granular fill. On the assumption that compaction should be considered as a transient surcharge pressure, Rowe noted negligible relaxation of stresses following removal of this surcharge. He therefore postulated that the full induced compaction pressures for rigid walls should be assumed to be retained following removal of the compaction plant.

2.2 Broms (1971)

Broms' assessment also focussed on the problem of rigid, smooth, vertical retaining walls. However, he applied the concept of a hysteretic stress path model in the derivation of an analytical solution. In this derivation, the soil was also assumed to be free draining and the backfill was assumed to have an at-rest pressure distribution prior to compaction. When the compaction plant acts on the backfill, it was assumed that the vertical stress was increased, following the elastic distribution with depth proposed by Boussinesq (1885). This was assumed to also bring a proportional increase in the lateral pressure distribution. Below a certain depth though, the soil stress remained unchanged, as the initial at-rest pressure distribution still governed.

After removal of the compaction plant, the vertical stress distribution largely returned to its initial values. The compaction induced plastic lateral strains in the soil though, leaving it over-consolidated. Broms proposed that the soil closest to the surface yields because of these high lateral stresses with removal of the compaction plant. He assumed that this reduced its lateral stress to a residual linear distribution, the slope of which was equal to the inverse of the at-rest earth pressure coefficient. Below a critical depth, this yielding was proposed not occur because the vertical confining pressures were greater. As such, below this critical depth, the soil retained its over-consolidated lateral stress distribution, and at a greater depth, still followed the initial at-rest pressure distribution.

On the expectation that the backfill was compacted in thin layers, he set out that the process described above was repeated. As the compaction effort was reapplied to the new backfill layer above, the vertical stress was predicted to again increase to the Boussinesq distribution; so too, a proportional increase in the lateral pressure. When the compaction plant was removed, only the soil closest to the new surface was assumed to yield to the residual linear distribution. This locked in the compaction pressures in the layers below as the backfill construction progressed up the wall. Simultaneously, with additional overburden placed through each subsequent layer, the at-rest earth pressure distribution that dominated at greater depth also followed the upwards migration of the backfill surface. Figure (1) describes the static lateral earth pressure distribution assumed to exist at the completion of this rigid wall construction.

2.3 Ingold (1979a; 1979b)

The analytical solution derived by Ingold (1979a) focussed on the problem of stiff, smooth, vertical walls with free draining backfill. Ingold largely followed the same methodology as that proposed by Broms

(1971), although he assumed that the initial stress distribution of the backfill followed that of an active state. Likewise, when the soil yielded following removal of the compaction plant, he assumed that the resulting residual pressure distribution was instead proportional to the inverse of the active earth pressure coefficient. Figure (1) also describes the static lateral earth pressure distribution assumed to exist at the completion of this stiff wall construction.

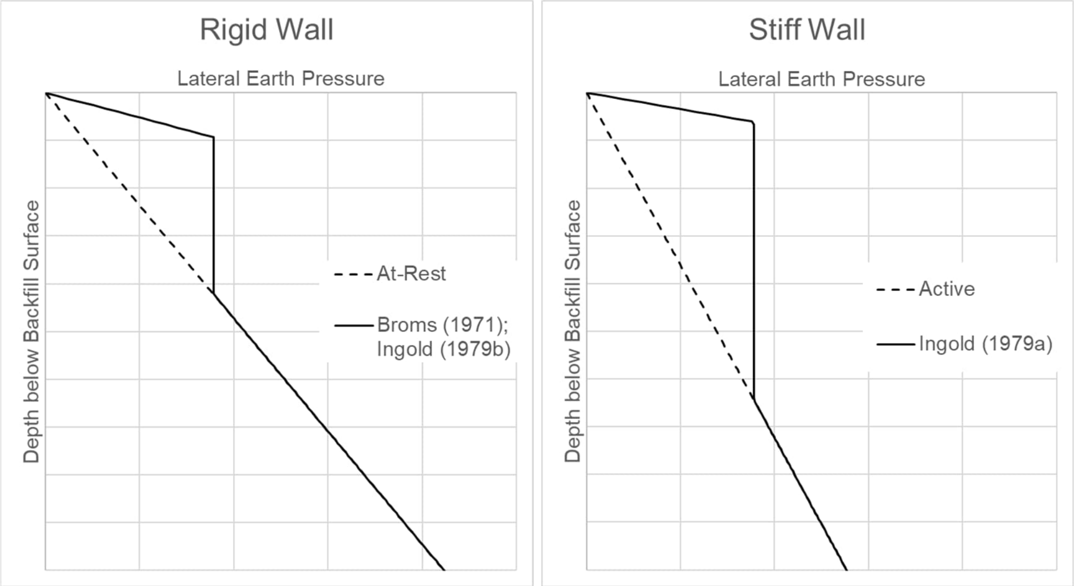

Figure 1. Lateral static earth pressure distribution with depth as proposed by Broms (1971) and Ingold (1979b) for rigid walls and by Ingold (1979a) for stiff walls.

Ingold (1979a) also presented a closed-form solution for this lateral pressure distribution with depth. To do so, he utilised an approximation for the compaction achieved by a dead-weight roller as originally proposed by Whiffen (1954). This assumed that the elastic stress distribution with depth during the compaction of a given layer was equivalent to that of an infinite line load. Whiffen (1954) found good agreement with this assumption from test results, even though the compaction plant itself was not infinite in length. Where vibratory rollers were utilised, Ingold (1979a) proposed that the uniform line load can be determined by “using an equivalent weight equal to the deadweight of the roller plus the centrifugal force induced by the roller vibrating mechanism.” This followed earlier work by Forssblad (1965).

In a subsequent paper addressing the problem of rigid, smooth, vertical walls with free-draining backfill, Ingold (1979b) proposed that the closed-form solution presented in Ingold (1979a) could still be used, but where the active lateral earth pressure coefficient was substituted for the at-rest coefficient.

2.4 Duncan and Seed (1986), Duncan et al. (1991), and Clough and Duncan (1991)

Duncan and Seed (1986) further expanded on the hysteresis stress path by Broms (1971) for a rigid, smooth, vertical wall. Modifications included the consideration of cyclic loading and unloading of the soil elements for each compaction effort. The model continued to assume that this loading was described by at-rest lateral earth pressure but utilised a coefficient that was modified as the over-consolidation ratio of the soil element changed with compaction. Likewise, the reloading curve modified with ongoing compaction although was always bounded by a Mohr-Coulomb passive pressure failure criterion.

The model was also further expanded to consider the increase in horizontal stresses from a “transient, moving, surficial load of finite lateral extent” (Duncan and Seed, 1986). This contrasted with the uniform line load of infinite length assumed by Ingold (1979a; 1979b). Through following an iterative process that lends itself easiest to Finite Element Modelling (FEM), the compaction-induced pressure distribution over the height of the wall could be evaluated.

Duncan et al. (1991) utilised a software program to develop design charts for different construction plant following the method of Duncan and Seed (1986). The pressure distribution curves were nonlinear over the depth of backfill in which compaction pressures dominated. The charts included both cohesive and cohesionless backfill, however, they noted caution regarding their adoption for cohesive material. Tables were also prepared to facilitate the modification of these pressure distributions for different variables.

Clough and Duncan (1991) stated that these charts should only be used for calculations when mechanical compaction equipment was anticipated within half the height of the wall, back from the wall. Likewise, they should only be applied to the design of vertical, rigid walls. For flexible walls, they noted that these pressures were likely to be conservative. Where movements as large as 0.4% were tolerable, they recommended that compaction-induced pressures be neglected for design.

2.5 Symons and Clayton (1992)

Symons and Clayton (1992) considered the application of existing compaction pressure theory on retaining walls with cohesive backfill. Utilising available test data, they concluded that the simplified methods of Ingold (1979a; 1979b) were in general inappropriate for cohesive material. This was due to the methods' fundamental assumption of free draining backfill. They did note though that the lateral pressure distributions after compaction of cohesive backfill were a function of the material's undrained shear strength. "Intermediate and high plasticity clay fills gave average horizontal total stresses on completion of filling of about 20% and 40% respectively of their undrained shear strengths" (Symons and Clayton, 1992). They also observed that reductions in this pressure distribution occurred with pauses in the backfilling operation because of stress relaxation.

Symons and Clayton (1992) also considered further the effect of time on these lateral earth pressures from cohesive backfill. In the case of rigid walls with intermediate plasticity backfill, these pressures were identified to reduce with time as the fill consolidated. The equilibrium distribution was concluded to be close to the at-rest state. Where swelling of cohesive backfill occurred, they recommended that the magnitude of these pressures must be determined experimentally. In the case of a rigid wall with high plasticity clay backfill, they noted that the equilibrium pressure distribution, following swelling, was close in magnitude to the limiting passive values. Lastly, they suggested that "problems due to swelling are likely to increase with the plasticity of the material" (Symons and Clayton, 1992).

3 DESIGN STANDARDS AND GUIDANCE

3.1 New Zealand

The primary compliance document for the design of structures in New Zealand, including retaining walls, is the New Zealand Building Code (MBIE, 2021a). It sets out that all buildings, building elements and sitework shall have a low probability of reaching an ultimate or serviceability limit state failure. The code requires that account shall be taken of all physical conditions that are likely to affect the design, including earth pressures (MBIE, 2021a). Compliance with this building code may be achieved through 'Acceptable Solutions', 'Verification Methods', or 'Alternative Solutions' although retaining wall design receives only brief coverage in Appendix C of Verification Method 4 (MBIE, 2021a). Hence, in demonstrating the compliance of retaining wall design, reference typically needs to be made to other design standards and guidance that discuss the topic of compaction pressures.

The authors are not aware of any New Zealand standards that specifically describe the determination of lateral earth pressures. However, recent design guidance is provided through the Earthquake Geotechnical Engineering Practice Module 6 (MBIE, 2021b) and the Bridge Manual (Waka Kotahi, 2022). The former specifically relates to earthquake resistant retaining wall design. Although it recommends consideration of surcharge loads in static design, no comment is made regarding compaction-induced pressures (MBIE, 2021b). The Bridge Manual does require the consideration of compaction earth pressures, although no specific prescription is made of how to determine them. However, a general reference is made to the Australian standard AS4678:2002 (Waka Kotahi, 2022).

An earlier New Zealand design guidance had commented on the use of compaction-induced earth pressures. The Works and Development Services Corporation (1990) recommended the adoption of the method of Broms (1971) and Ingold (1979a) for the calculation of compaction-induced earth pressures on rigid and stiff retaining walls respectively. The guide also made the distinction that "translations or rotations in the order of H/500, where H is the height of the wall, may reduce compaction-induced pressures to those of the active state." Hence "free standing relative flexible walls… on soil foundations need only be designed for active pressures" (Works and Development Services Corporation, 1990). However, it also noted that due to the extent of wall displacement that occurs, a parabolic (rather than triangular) earth pressure distribution may result with a corresponding increase in bending moment of 50%. Nonetheless, the authors are not aware of continued widespread use of this guide in New Zealand.

3.2 International

Internationally, there are multiple standards and guidelines concerning the determination of lateral earth pressures for the design of retaining walls. AS4678-2002 Earth-Retaining Structures (Standards Australia, 2002), for example, includes a succinct commentary on the nature of compaction-induced earth pressures. The standard includes construction considerations such as the selection of compaction plant behind a retaining wall and recommends the method of Ingold (1979a; 1979b) for estimating these pressures for rigid and stiff walls. Likewise, the recommendations of the Hong Kong Geoguide 1 – Guide to retaining wall design (Government of the Hong Kong, 2000) are similar.

Eurocode 7 notes a requirement to consider the effects of compaction-induced earth pressures, although makes no mention of methods upon which this calculation should be based. Instead, it emphasises the specification of appropriate compaction procedures to avoid unacceptable movements (European Committee for Standardization, 2013). AASHTO recommends in the LRFD Bridge Design Specifications (2020) the use of the design charts prepared by Duncan et al. (1991) as presented in Clough and Duncan (1991).

4 APPLICATION TO NEW ZEALAND PRACTICE

Retaining walls in New Zealand commonly employ the use of compacted backfill in their construction. Generally, the backfill used is a well graded, cohesionless sandy gravel with back-of-wall drainage measures installed. An absence of detailed commentary from New Zealand standards and guidelines on compaction-induced earth pressures though means that practitioners require access to other design references. However, the international design standards and guidelines identified above are well-suited to this typical backfill construction.

In some regions of New Zealand access to such premium aggregates can be limited. There can instead be a desire to utilise more readily available, locally sourced finer grained backfill. Whilst this is unlikely to extend to high plasticity clays, the presence of an elevated fines content alone could introduce the potential for generating excess pore water pressures during construction. This desire may also increase in the coming years as carbon-reduction considerations grow in importance for civil engineering projects. A heightened awareness amongst practitioners of the consequences of such a decision is therefore required. In the authors' opinion, it is not immediately evident that the identified design standards and guidelines highlight these risks sufficiently.

Vibratory plates and rollers are common methods for the compaction of this backfill and hence have the potential to introduce significant lateral stresses and deflections into the constructed works. As noted by Forssblad (1965), the induced stresses from such vibratory plant are significantly greater than dead-weight plant. In the authors' experience, specification of limits to the proximity of these plant to these walls during construction is rare. So too, are recommendations to adopt smaller or non-vibratory plant in immediate proximity to the wall. The opportunity therefore exists to reduce the compaction-induced pressures requiring consideration through refinement of this construction practice. In such an absence, retaining wall designs in New Zealand should be considering the potential for use of large vibratory plant during construction.

For much of New Zealand, due to the presents of earthquake hazards, seismic considerations typically govern the design of moderate to high importance retaining walls. Nonetheless, to fully appreciate the consequences of seismicity on the structure, its condition under static loading also needs to be understood. Appropriate incorporation of the effect of compaction pressures is therefore necessary to ensure that the structure does not exceed its deflection tolerances or internal structural capacity when later subjected to the additional demands of seismic loading. This relationship does not appear to be strongly presented in the design standards and guidelines identified. Greater awareness amongst New Zealand practitioners of compaction-induced earth pressures is therefore recommended.

5 CONCLUSION

Testing over many decades has identified that the classical theories of lateral earth pressure often underestimate the measured values where backfill is placed and compacted behind retaining walls. Several models for this compaction-induced earth pressure have been developed by others. For rigid and stiff walls, where wall deflection is limited, the models present an increase in the stress distribution to be resisted by the structure. For flexible walls, where deflection is not constrained, the models present an increase in that deformation. It is evident from a review of existing literature that consideration of compaction-induced pressures can be critical in the static design of retaining walls. Where it isn't adequately considered in design, excessive deformation of the wall or internal structural failure may eventuate. This is also the case where the design is governed by seismic considerations, as the wall may be closer to its structural capacity or deflection tolerances, under static loading alone, than would otherwise be expected.

Commentary on the subject in current New Zealand standards and guidelines is limited and this should be addressed to promote consistency across the industry. Likewise, the recommendations of commonly used international design standards, such as AS4678:2002, are typically appropriate for the use of free draining backfill only. Whilst such a backfill is common for construction in New Zealand, there is limited guidance on compaction-induced pressures where cohesive backfill is selected. As such, there is a risk that these considerations are not fully understood by practitioners if they do compromise on backfill quality. This too should be addressed in updated New Zealand guidance. Furthermore, this updated guidance should promote opportunities to reduce these loads, such as through the specification of smaller non-vibratory compaction plant during construction in the immediate proximity of the wall.

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