LATERAL EARTH PRESSURE ON NON-YIELDING WALLS SUPPORTING OVER-CONSOLIDATED SAND

by

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Approval Signatures

We, the undersigned, approve the Master’s Thesis of Amin Bigdeli.

**Thesis Title:** Lateral Earth Pressure on Non-Yielding Walls Supporting Over-Consolidated Sand

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To my Parents

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ABSTRACT

The most important problem associated with retaining wall structures is the additional compaction-induced lateral earth pressure. Currently, none of the available design methods used to calculate the lateral earth force on non-yielding walls can explicitly consider the compaction-induced lateral force. Therefore, there is a need to quantify the compaction-induced lateral earth force and modify the current design methods to consider this additional force. To achieve this objective, a numerical model was developed using the program FLAC and was validated against carefully conducted experimental tests. Material properties such as backfill soil friction angle, wall panel elastic modulus, and sand degree of consolidation (compaction), were varied between the numerical models to isolate their effects on the wall responses. Effects of these properties on the lateral earth pressure magnitudes and distributions, wall lateral deflection, horizontal vertical earth force, and the location of the resultant earth force were investigated. Results indicated that increasing the friction angle of the backfill soil, elasticity of the wall, and inclination of model wall facing the panel resulted in a decrease in the lateral deflection of the wall panel. The location of the resultant lateral force increased when the friction angle of backfill soil increased. On the other hand, increasing the degree of consolidation of the backfill soil as well as the elasticity of facing panel lowered the location of the resultant force acting on the wall. For dynamic responses, the maximum dynamic and residual lateral deflection increments increased with the backfill soil friction angle and decreased with both the sand backfill consolidation ratio and the wall panel elastic modulus. Both dynamic and residual earth pressure distribution were different from the static distribution, regardless of the material properties. The location of the resultant force was slightly affected by the backfill soil degree of consolidation and wall panel elasticity. A comparison between theoretical and numerical results indicated that the distribution of earth pressure resulting from over-consolidated sand on non-yielding walls is not hydrostatic nor does it follow the traditional Jaky’s formula.
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Chapter 1: INTRODUCTION

1.1 Earth Retention Systems

Retaining walls are used extensively in the Middle East, Gulf countries, and around the world. They are being used in structures such as basements, tunnels, flood walls, and highway bridges. Retaining walls are classified structurally into four different types: gravity walls, piling walls, cantilever walls, and anchored and reinforced walls. Figure 1.1 summarizes the types of retaining walls found in the literature.

Gravity walls (Figure 1.1a) are the oldest type of retaining wall. These walls depend mainly on their own weight to resist the soil lateral earth pressure. The wall should be checked for stability against sliding, overturning, and bearing capacity failure modes. This type of retaining wall is heavy and costly. In addition, these types of retaining walls are not suitable for soil with a low bearing capacity, such as soft clay or loose sand. The cantilever wall (Figure 1.1b) gains its stability from the weight of the soil overlying its base in addition to its own weight. It should be safe against all modes of failure described for gravity retaining walls. In addition, cantilever retaining walls should be designed to resist shear force and bending moment developed due to the imposed lateral earth pressure. Figure 1.1c shows the other type of retaining system which is the sheet pile wall. In this wall type, the penetration depth is the major factor that provides the wall with the stability against failure. The penetration depth of the wall into the soil creates a passive force which cancels out the active force imposed by the retained soil behind the wall. The wall in this case should be able to resist bending moments that develop due to the fixation with the soil at the penetration depth. In an anchored wall (Figure 1.1d), the wall prevents the failure due to sliding and over-turning by having the reinforcements into the retained soil behind it. This method can be combined with all types of retaining walls to get the more resistance to retain the soil.
Three types of lateral earth pressure can be exerted on retaining walls: at-rest, active, and passive earth pressure. Based on the movement of the retaining wall, these different types of earth pressure can be developed. Active and passive lateral earth pressure develop when the wall movements are enough to mobilize the soil full shear strength capacity. When the retaining wall is able to move freely and soil mass is sufficiently strained to mobilize its shear strength, active earth pressure is developed on the wall. If the movement of the retaining wall causes the soil to get compressed and mobilize shear strength, passive earth pressure is created. This passive compression usually happens in
the cases where there are soil deposits in front of the retaining wall that are forced to move forward due to the pressure coming from backfill soil. This passive earth pressure behaves as a resisting force to the active movement of the retaining wall. Different types of retaining wall movements are shown in Figure 1.2.

At-rest earth pressure is developed when there is no lateral moving of the retaining walls or the lateral movement is not enough to develop the shear strength capacity of the soil. This condition usually happens when the top and bottom of the wall is braced and prevented from any movement. Basement walls are example of these types of retaining walls which are fixed with the foundation at the toe and braced at the top with the concrete floor slab. These walls are usually called non-yielding walls.

![Figure 1.2: Different Types of Retaining Wall Movement](image-url)
1.2 Problem Definition

The behavior of non-yielding retaining walls is one of the important topics in geotechnical engineering and the interaction between soil backfill together with the retaining wall is very complicated. In order to resolve some of these complications, the earth pressure distribution behind the non-yielding retaining wall should be analyzed interactively with the lateral deflection of the wall. Due to the complexity, the lateral earth pressure for at-rest, active, or passive conditions are assumed to have a triangular shape with a resultant force location at $H/3$. ($H$ is height of the retaining wall). This method can be true for walls which develop sufficient lateral movement to produce a soil failure wedge. In other words, retaining walls which have sufficient horizontal movement at the base or rotate around the toe could be analyzed using the assumed triangular shape for lateral earth pressure. In the case of non-yielding retaining walls, due to the lateral restraint at the top and bottom of the wall, the shear strength of the backfill soil is not sufficiently mobilized to create static active or passive earth pressure on the wall.

The use of non-yielding retaining walls in civil engineering is very extensive. Tunnels, piles, basements, and bridge abutments are typical examples of non-yielding walls due to the lateral restraint at the top and bottom of these structures. In these types of structures, the wall is not allowed to move to produce active and passive earth pressure. Figure 1.3 illustrates examples of non-yielding retaining wall structures used in civil engineering work.

The most important problem associated with these structures is the compaction-induced lateral earth pressure which produces additional lateral earth pressure. This additional lateral earth pressure is not explicitly considered in the current design methodology. This problem becomes significant when the backfill is dry sandy soil, and the wall is closer to a source of vibration (e.g. highways or seismically active areas).
Figure 1.3: Different Types of Non-Yielding Retaining Wall Structures [2]
1.3 Research Objectives

The objectives of this study can be summarized as follows:

- Scale up the numerical model developed by El-Emam in order to simulate a full height non-yielding wall in prototype size [2, 3].
- Use the scaled-up numerical model to carry out static and dynamic analyses for non-yielding walls with different geometries and material properties in prototype scale.
- Investigate the magnitude and distribution of lateral earth pressure behind non-yielding retaining walls under both static and dynamic loading conditions.
- Find the location of the lateral earth force behind non-yielding retaining walls for both static and dynamic responses.
- Compare the current at-rest earth pressure theory with the numerical results from this study.

1.4 Research Methodology

The experimental tests, which were conducted at the Royal Military College of Canada (RMCC) [2, 3], provided reliable quantitative results for values of earth pressure at-rest ($K_o$). The static tests were used to calibrate a numerical model developed using the FLAC software package. The numerical model was able to capture both the magnitude and distribution of the at-rest lateral earth pressure. During the current investigation, this numerical model was calibrated against the static response of a non-yielding experimental model wall. After calibration, the model wall was scaled up to simulate a full-scale retaining wall in at-rest conditions. Then the scaled up model walls were subjected to real-input-based excitation. Different model wall parameters such as wall height and stiffness and soil types were investigated for their effects on the wall responses. The effect of both geometrical and material parameters on the model wall response such as lateral deflection, lateral earth pressure and forces, and vertical forces at the base of the wall were investigated and discussed. The results from static conditions were compared to the current design methodologies, and the sources of conservativeness or non-conservativeness were defined.
1.5 Thesis Organization

Chapter 2 presents the active/passive earth pressures and their distribution behind the retaining walls. Next, it gives details about Coulomb and Rankin’s method, their differences, and limitations in calculating the earth pressure. The next section explains the Jaky’s earth pressure theory [4], its simplified equation, and the assumptions and limitation of this method. The effects of vibratory-induced compaction of backfill soil are explained in Chapter 2. The last section presents a review of previous numerical studies of non-yielding retaining walls with over-consolidated backfill soil under both static and dynamic loads. Finally, Wood’s solution [5] and FEM are described together with the experimental and numerical study of El-Emam [2, 3].

Chapter 3 describes in more detail the experimental and numerical models developed by El-Emam [2, 3]. It also introduces a step-by-step description of how the numerical simulations were developed using the commercially available dynamic finite difference program FLAC [4]. Comparisons between numerical and experimental results were conducted to verify the accuracy of the model. In the last section, the calibrated numerical model was used together with Iai similitude to develop a prototype wall with 4 m height [5].

Chapter 4 presents the results of the effect of geometrical and material properties of model walls on static responses of non-yielding retaining walls. For each model, the lateral deflection of the model wall, besides earth pressure distribution, were plotted and compared with Jaky’s or modified Jaky’s formulas [4]. Lastly, the effects of each parameter on horizontal and vertical earth force as well as the location of the resultant force were studied.

Chapter 5 examines the effect of material properties on dynamic behavior of non-yielding walls at prototype scale. The results are presented and discussed with respect to lateral deformation in the model walls, horizontal and vertical earth forces at the bottom of the wall and the variation of resultant force location due to change in material properties.

Finally, Chapter 6 summarizes the numerical findings, implications for current seismic design methods for non-yielding retaining walls supporting over-consolidated sand, and presents some recommendations for future research.
Chapter 2: LITERATURE REVIEW

2.1 Earth Pressure Coefficient

The coefficient of earth pressure at-rest, $K_o$, is defined as the ratio between the effective horizontal stress and effective vertical stress [6]:

\[ K_o = \frac{\sigma_h'}{\sigma_v'} \quad (2.1) \]

Lateral earth pressure acting on a retaining wall is an essential parameter needed to study the stability of the wall. In addition, the accurate estimation of lateral earth pressure depends on calculating a precise value of $K_o$. Bishop [7] provides a more specific definition for the coefficient of earth pressure at-rest. According to this definition, where the soil is consolidated under the condition of no lateral deformation, $K_o$ is defined as the ratio of the lateral to the vertical effective stresses. At this condition, “the stresses state is principal stresses with no shear stress applied to the planes on which these stresses act” [7]. Other researchers have presented new meanings for the coefficient of earth pressure at-rest when no strain occurs in the direction of the minor principal effective stress. In this condition, the ratio of increments of minor to major principal effective stress is called the “coefficient of earth pressure at-rest” [8].

The active earth pressure state is generated when soil mass expands and strains downward due to the free tilt of the retaining wall. The traditional solutions to calculate the pressure on the retaining wall with active state are to use either Rankin’s or Coulomb’s formulation. The parameters needed for both Coulomb’s and Rankin’s method can be easily determined by conducting conventional laboratory tests. Both of these formulations assume a triangular earth pressure distribution, with the maximum value at the lowest point of the wall, and extended up to the crest of the wall. These studies assumes a linear variation of the lateral earth pressure acting on the wall, and the resultant force is usually taken at 1/3H from the bottom of the wall.
Much experimental evidence [9, 10] has proven that the earth pressure distribution on retaining walls is not linear, and depending on wall movement relative to the soil (i.e., sliding, rotation about the top, and rotation about the heel) earth pressure distribution can take different shapes. Another researcher [11] stated that the non-linearity of the active earth pressure distribution may be the result of backfill soil arching effects. For this reason, the stress near the top of the retaining wall might be increased beyond the level of the active state and as a result, the location of the resultant earth pressure will be much higher than 1/3 from the base of the wall.

Terzaghi [12] illustrated the concept of arching by having a large box of soil with a moveable panel at the bottom (Figure 2.1). If the soil is relatively loose, (i.e., soil with low shear strength), it immediately tends to move down as soon as the panel below moves downward. However, in the case of relatively dense soil (i.e., soil with sufficient shear strength), when the panel moves downward, the soil column above the panel transfers some of its stresses to the surrounding soil. Therefore, the vertical stress in the column of soil above the panel is decreased, while the stress around the moving panel is increased. The redistribution of stress in which soil transfers some of its stresses to the surrounding region of soil mass is called “arching.”
Figure 2.1: Stress Redistribution Caused by Arching Phenomena in Soil [12]

The soil local arching phenomenon explained earlier results in a parabolic distribution of earth pressure for soil in contact with a relatively flexible retaining wall restrained from lateral movement at both ends. Jaky [13] used the soil arching effect to derive his well-known “at-rest” earth pressure theoretical formula. The equation below was proposed by Jaky in order to calculate the value of $K_o$ based on the effective angle of internal friction:

$$K_o = \frac{(1+\frac{2}{3}\sin \phi')}{(1+\sin \phi')}$$

(2.2)

Where $\phi'$ is the effective friction angle. Equation 2.2 was simplified to take the following approximation:

$$K_o = (1 - \sin \phi')$$

(2.3)
Figure 2.2: Comparison of Jaky’s Equation and Simplified Jaky’s Equation for Estimating, $K_o$ for Normally Consolidated Soils [4]

Figure 2.2 shows the comparison of Jaky’s equation and a simplified Jaky’s equation for estimating $K_o$ for normally consolidated soils [4]. It proves that Jaky’s theoretical equation (Eq. 2.2) is not in complete agreement with the values calculated from the simplified equation (Eq. 2.3). The difference between these equations is less (around 9%) at low friction angles and increases (goes to 16%) as the friction angle rises. However, the difference is not significant and can be neglected. On the other hand, considering the ease of use for the new method (Eq. 2.3) in comparison to Jaky’s theoretical equation (Eq. 2.2) which requires that an appropriate choice be made of $\phi'$ for a given soil, this much difference can be neglected. Therefore, this method is safe to use for engineering purposes [15]. As a result, the literature suggests using Jaky’s simplified equation (Eq. 3) to calculate the value of $K_o$. Also, as reported by some researchers, for loose and normally-consolidated soils, the simplified Jaky’s equation is practically accepted as the horizontal-to-vertical stress ratio [16, 17, 18, 19]. However, both static and dynamic compaction efforts increase the magnitude of at-rest stresses [20].
2.2 Compaction Effects on Lateral Earth Pressure

Rising the magnitude of lateral stresses of the soil is one of the important results of vibratory compaction which is not paid enough attention [21]. Sand fills (such as hydraulic fills) are usually normally consolidated prior to compaction. It was understood through some experiments that lateral earth pressure and deflection of retaining structures are affected significantly with compaction [6]. Compaction can increase the lateral earth pressure significantly. Therefore, an ability to analyze such compaction effects is necessary in order to properly model the response of retained compacted soils at both static and dynamic loads. Compaction-induced earth pressures affect the stresses exerted on the structure. As a result, any change in structural stresses leads to different deformation which is a serious concern in the design and analysis of many types of soil-structure systems. Some of these types of structures are:

1) Retaining walls
2) Buried structures and pipes
3) Flexible culverts
4) Tunnels

In addition, compaction-induced stresses also influence resistance to liquefaction and hydraulic fracturing within a soil mass, as well as stress distributions and deformations of compacted earth and rock fill dams and embankments. Based on the field data available in the literature, the following general observations can be made regarding compaction-induced stresses and deformations:

- Compaction of soil represents a process of application and removal of load which can result in a significant increase in residual lateral earth pressures. These earth pressures may be significantly greater than the theoretical at-rest values, and may approach passive earth pressure magnitudes [22, 23, 24].
- The depth to which compaction increases lateral earth pressures appears to be a function of the dimensions and vertical thrust of the compaction roller, varying from an order of 2 to 3 meters for small hand-operated vibratory rollers, to as much as 15 meters for very heavy compaction equipment [23, 25].
- The compaction of soil against deflecting structures can significantly increase structural deflections [26]. Compaction generally increases near-surface residual
lateral pressures to greater than at-rest values, and generally decreases lateral pressures at depth, apparently as a result of increased structural deflections. “The mode of structural deflections can, however, significantly influence this pattern” [27].

- Compaction of the soil has a diminishing effect on increasing the earth pressure. This means that any further compaction effort on the locked-in soil particles (soil with a history of compaction) increases the peak earth pressure in smaller increments than in un-compacted soils. It was proven that a negligible fraction (40% to 90%) of this peak increase may be retained as residual earth pressure increases upon the completion of compaction [17, 25].

Several theoretical and analytical methods have been proposed to explain the residual lateral earth pressures induced by soil compaction. Common to all of these is the idea that compaction represents a form of over-consolidation wherein stresses resulting from a temporary or transient loading condition are retained to some extent following removal of this peak load [28]. Compaction can be considered application and removal of a surficial surcharge pressure. Rowe [27] stated that the soil stresses induced by the surcharge loading would be retained after surcharge removal. Rowe suggested that the coefficient of lateral earth pressure in a soil following compaction could be expressed as [27]:

\[ K'_o = K_o \left( 1 + \frac{h_o}{h} \right) \]  

(2.4)

In equation 2.4, \( K_o \) is the coefficient of earth pressure at-rest, \( h \) is the overburden pressure, and \( h_o \) is the effective transient overburden pressure representing the peak loading condition during the compaction process. Moreover, another similar theory based on sliding planes within the soil mass and strain reversal was proposed in [24].

Many studies have been done on at-rest earth pressure distribution on retaining walls. These studies can be categorized into two parts:

- Quantitative studies on reduced-scale model walls [10, 20, 29, 30].
- The Finite Element Method (FEM) done to investigate more about the earth pressure distribution [31, 32, 33].
Researchers developed a theoretical model to predict pressure and wall deflection produced during compaction [34]. They implemented an incremental finite element scheme to model the backfill compaction. It was determined that compaction significantly affected the magnitude and distribution of earth pressure. The resulting earth pressure distribution was found to be non-linear, with final values as much as twice the initial values for the top half of the stem (Figure 2.3)

![Earth Pressure due to Compaction](image)

**Figure 2.3:** Earth Pressure due to Compaction, Estimated from a Numerical Analysis [34].

The over-consolidation ratio (OCR), which is the previous stress history of the retained soil, is one of the most important factors that influences the value of the coefficient of at-rest earth pressure. Many experiments conducted on different consolidated soil deposits proved that the range of the $K_o$ value is between 1 and 2. In addition, many studies on soil deposits proposed an empirical relationship to calculate the coefficient of earth pressure at-rest for over-consolidated sand [15]:

$$K_o = (1 - \sin \phi')OCR - \left(\frac{\mu}{1 - \mu}\right)(OCR - 1)$$  \hspace{1cm} (2.5)
Where $\mu$ is Poisson’s ratio. Mayne and Kulhawy [19] provide an excellent summary of the effects of stress history on $K_o$. The data of over 150 different soils tested was analyzed and summarized. Then, these results were used to conduct a statistical analysis to study the relationships between at-rest earth pressure and stress history. They concluded that Jaky’s formula agreed very well with the test data for normally consolidated soils. A relationship between $K_o$ and $OCR$ built on Jaky’s simplified equation was provided by analyzing the unloading portion of the stress path. Therefore, Equation 2.3 can be rewritten as:

$$K_o = (1 - \sin \phi') OCR \sin \phi'$$  \hspace{1cm} (2.6)

where $OCR$ is the over-consolidation ratio. Figure 2.4 illustrates the variation of $K_o$ with the soil friction angle $\phi'$ at different $OCR$ values.

Figure 2.4: Variation of $K_o$ with Soil Friction Angle at Different Over-Consolidation Ratios
Prior to compaction all sand fills are normally consolidated and the value for the earth pressure coefficient \( K_o \) usually follows the same value of the earth pressure coefficient calculated using Jaky’s equation. According to some studies, subsequent vibratory compaction increases the lateral earth pressure significantly [35, 36, 37, 38]. Additionally, it was found that the value of the coefficient of earth pressure at-rest is increased due to laterally-constrained densification of normally consolidated sand [19]. This densification of sand occurs by vibration under an effective overburden pressure. This increase in earth pressure was first quantified by Peck and Mesri [39]. They realized that the lateral earth pressure was very close to the value of passive lateral earth pressure, near the backfill surface. While in the wall bottom, the lateral earth pressure was related to normally consolidated at-rest conditions.

Experimental tests were conducted to measure the lateral earth pressure of sand backfill after compaction using CPT [21]. The researchers concluded that vibratory compaction has a significant effect on increasing the lateral earth pressure. Another experimental test was conducted on non-yielding retaining walls using the shaking table and Ottawa sand to simulate the effects of compaction on the lateral earth pressure of loose sand and compacted sand [40]. It was concluded through this study that for loose sand the lateral earth pressure increases linearly with the depth; this value was also found to be in good agreement with Jaky’s formula as shown in Figure 2.5. For the dense condition, loose sand was placed and compacted in five lifts using shaking table vibration. The measured distribution of horizontal earth pressure against the non-yielding wall after the compaction of each soil lift is shown in Figure 2.6. Based on the experimental data obtained during this investigation, it was concluded that after compaction, the lateral earth pressure measured near the top of the wall was almost identical to the passive earth pressure estimated by the Rankin theory [40].
Figure 2.5: Distribution of Horizontal Earth Pressure against Model Non-Yielding Wall for Loose Sand [40]
Figure 2.6: Distribution of Horizontal Earth Pressure after Compaction [40]
Many studies have shown that the compaction of soil increases the lateral earth pressure exerted on non-yielding structures. It was proved that compaction has a larger impact on near-surface residual lateral earth pressure and as the depth is increased, this effect is diminished [32]. In addition, during compaction there is a 40% to 90% incensement in horizontal earth pressure which may be locked-in as residual pressures (as stated before) [20]. The researchers attributed this to the increase in the structural deflections close to the top. Therefore, in the case where heavy compaction is applied to soil deposits, it can be concluded that horizontal stress can exceed the vertical stress.

![Figure 2.7: Change in Vertical and Horizontal Earth Forces on a Non-Yielding Wall due to First, Second, and Third Vibration Effort [3]](image)

Compaction of the soil has a diminishing effect on increasing the earth pressure. This means that any further compaction effort on the locked-in soil particles (soil with a history of compaction) increases the peak earth pressure in smaller increment than in uncompacted soils. It was found that a negligible fraction of this peak increase may be retained as residual earth pressure increases upon the completion of compaction [17, 25]. El-Emam confirmed this conclusion experimentally by shaking over-consolidated sand adjacent to non-yielding sand [3]. Results shown in Figure 2.7 indicate that the second
and third vibration slightly affect the horizontal and lateral earth force developed at the footing of the non-yielding wall.

Many experiments conducted to measure the coefficient of lateral earth pressure at-rest proved that Equation 2.6 under-estimates the values of $K_o$ by 3.5% compared to average measured values, which is practically acceptable. Furthermore, researchers studied the effect of the OCR of sand [41]. They concluded that Equation 2.6 is in agreement with experimental values in predicting $K_o$ up to an $OCR = 3.0$, whereas the theoretical values underestimated $K_o$ thereafter. The theoretical values of Worth were about 10% to 15% higher than the experimental values for $OCR < 3.0$, whereas they were 10% to 12% lower thereafter [15].

Despite the popularity and ease of use of Jaky’s theoretical and simplified equation (i.e. Equations 2.2 and 2.3), they only consider the effect of soil friction angle, $\phi$, in calculating the coefficient of earth pressure at-rest, $K_o$. However, this is not correct for backfill soils with $OCR > 1$. In addition, recent studies proved the dependency of the $K_o$ value on soil deformation [42]. Therefore, ignorance of the soil over-consolidation ratio along with soil deformation in calculating $K_o$ creates a major deficiency in the application of Jaky’s formula. As a result, the effect of over-consolidation along with deformation within the soil mass must be considered to represent a correct equation to predict the $K_o$ value.

In order to study the effect of vibratory compaction on lateral earth pressure, an experiment was conducted on vertical non-yielding walls using a shaking table developed at the Royal Military College of Canada (RMCC) [2, 3]. Different load cells were designed at the top and bottom of the model to measure the total vertical and horizontal loads and deducing it to obtain the values of at-rest earth force, $P_o$. Figure 2.8 illustrates a comparison between the values of at-rest earth force with the values calculated using the equation proposed (Equation 2.6) which proves the good agreement between these two values for sandy soil with $OCR = 4$. Therefore, the old Jaky’s formula (i.e., Equation 2.1) largely underestimates the at-rest earth pressure coefficient for over-consolidated sand (i.e., $OCR > 1$). More details about the experimental model will be introduced in Chapter 3, as these tests are used in the current study to calibrate the numerical model of the non-yielding wall.
2.3 Dynamic Earth Pressure on Non-yielding Retaining Walls

Practically, non-yielding retaining walls are restrained horizontally, and therefore do not make sufficient movement for the shear strength of the backfill soil to be completely mobilized. Therefore, the limiting dynamic active and passive earth pressures cannot be developed. Some examples of non-yielding retaining walls are tunnels, basements, and foundations of bridges. Also, some retaining walls, due to their massive weight with foundations on firm rock or dry docks, are sometimes referred to as non-yielding retaining walls.

In geotechnical engineering, the correct estimation of earth pressure on retaining structures is necessary in order to have safe and economically-designed retaining walls, braced excavation, sheet pile, etc. The complexity in analysis of these structures (for both static and dynamic conditions) has caused this topic to attract many researchers in soil mechanics and geotechnical engineering fields. Throughout the decades many theories have been proposed for the estimation of seismic earth pressure. Mononobe-Okabe is the oldest and most commonly used method which is a pseudo-static force-based approach [43, 44]. This method does not include the frequency and is only dependent on the maximum peak ground acceleration amplitude (PGA). It also assumes relative
movements of the wall and soil, large enough to induce a limit or failure state in the soil, and hence full mobilization of earth pressure is assumed in the analysis. Recent methods of estimating the seismic active earth pressure of retaining walls using pseudo-static force-based were proposed [45, 46]. In both methods, it was assumed that the movement of the retaining wall reaches its limiting state. However, even in static cases, full mobilization of earth pressure depends on the displacement of the wall and partial mobilization is more common in most of the cases [47, 48].

A mathematical model was proposed to estimate the response of both systems bounded by two boundaries and semi-infinite system. These boundaries were designed to prevent the wall to have small translational modes of movement [49]. However, this method has two shortcomings:

- It was assumed that there is no shearing resistance for the soil close to wall. This assumption may change the resulting earth pressure on the wall [50].
- The value of active earth pressure depends on the stiffness of the springs between the far-field and the wall. Therefore, any error in estimating the stiffness of the spring would result in an enormous change of the dynamic active earth pressure on the wall.

Two different analytical approaches to analyze the earth pressure on non-yielding walls were found in the literature. To overcome the disadvantages of the explained model, Wood proposed an analytical solution based on finite element results for soil retained between two vertical walls [51]. He highlights the effects of several parameters such as the frequency of vibration on the seismic soil pressure magnitude and distribution. A method was proposed to estimate the dynamic lateral earth pressure on non-yielding walls [52]. The following sections introduced the main features of both methods explained earlier.

2.3.1 Wood’s Solution (1973) [5]

Assuming the backfill soil as an elastic material, Wood analyzed the response of a non-yielding retaining wall for both a uniform modulus and a modulus that varies linearly with depth [51]. This study could prove that dynamic amplification becomes an important factor where the input motion’s principal energy approaches the fundamental
frequency of the unrestrained backfill \( (f_o = V_s/4H) \). However, if the input motion frequency \( f \) is less than \( 0.5f_o \), the dynamic amplification is negligible and the static elastic solution is accurate in finding the pressures, forces, and moments on non-yielding retaining walls under harmonic excitation of cyclic load with frequency \( f \). In calculating the first mode of vibration, the backfill is considered as a semi-infinite layer of depth \( H \) [51]. Although the value of \( f_o \) depends only on \( V_s \) and the geometry of the backfill, \( f = 0.5f_o \) usually covers all practical cases. In this range and for the case of a uniform, constant, horizontal acceleration throughout the soil, wall pressure can be calculated from the elastic solution. Wood considers backfill soil as a homogeneous material that behaves like linearly elastic material. Therefore, Wood presents a method to calculate dynamic lateral forces and moments for a rigid wall by assuming that seismic excitation is due to a uniform, constant, horizontal acceleration throughout the backfill. Wood actually considered two rigid walls separated by a distance \( L \) of sufficient magnitude to avoid interaction between the two of them (Figure 2.9). The dynamic force and moment are calculated according to Wood’s method as:

\[
\Delta P_{oe} = \gamma H^2 \frac{a_h}{g} F_p \\
\Delta M_{oe} = \gamma H^3 \frac{a_h}{g} F_m
\]

Where \( a_h \) is the amplitude of the motion. The dimensionless factors \( F_p \) and \( F_m \) are shown in Figure 2.10. Wood showed that the lateral seismic force against the wall in cases of wide backfill were acting at 0.63H above the base of the retaining wall. The point of application of \( \Delta P_{oe} \), above the base of the wall, is given by:

\[
z = \Delta M_{oe} = 0.63H
\]
Figure 2.9: Configuration of Non-Yielding Wall for Calculating Dynamic Loads on Rigid Retaining Walls

Figure 2.10: Earthquake-Induced Soil Pressures on Structures [51]
Stress distribution on the back of the wall is the function of the lateral extent of the backfill material and Poisson’s ratio and is shown by the ratio of width of the backfill on the height of the wall \((L/H)\). If the value of \(L/H\) is equal to 10, it corresponds to backfills with large widths; and if the value of \(L/H\) is equal to 1, then it corresponds to narrow width backfill. The resulting horizontal stresses have larger values along the upper half and smaller values along lower half of the retaining wall. The shape of this horizontal stress distribution is parabolic. It was proved that \(\sigma_x\) has a larger value for wide elastic backfills and a lower value for narrow backfills.

Although Wood’s approach has a very simplified procedure compared to other methods, it has some limitations. Wood’s procedure does not account for:

1) Phase response at any given time  
2) Acceleration on vertical direction  
3) Increase of modulus with depth in backfill  
4) Other loads applied on the surface of the backfill  
5) Effect of level of shaking on reduction of soil stiffness  
6) Acceleration amplification through the backfill height

2.3.2 Ostadan and White (1998) [48]

The Mononobe-Okabe (M-O) method is one of the oldest solutions for the design of earth retaining walls. This technique which is based on Coulomb’s theory of static soil pressure development has many assumptions that make it not applicable to design all types of retaining walls. This method is proposed for dry cohesionless backfill soil retained behind a wall which can develop active wedge pressure. On the other hand, M-O does not take the nonlinearity effect of backfill soil into account. Due to these limiting assumptions, many researchers have conducted experimental and analytical studies to verify the adequacy of this method in the design of retaining walls. Wood proposed a method for non-yielding retaining walls, which because of their fixation at the bottom and top, is not able to move and create active wedge pressure. Although Wood’s solution [5] includes the effect of more parameters in the design of non-yielding retaining walls, in some cases the amplification of motion in soil mass (due to nonlinearity of soil particles) plays a significant role [53]. As a result, a new approach was proposed for the
calculation of dynamic earth pressure which considers motion amplification and the
effect of frequency on the magnitude and distribution of soil pressure [50]. However, the
complexity of this method has made it uncomfortable to use in the design of walls.

Recent studies have shown the significant role of soil-structure interaction (SSI) on
dynamic earth pressure exerted on the retaining wall. This means that not only the
backfill soil properties, but also the structural properties, size of the structure, and
foundation embedment also affect the seismic soil pressure on the wall [54]. Ostadan [50]
investigated a new approach with consideration of:

- Limited deformation of the wall due to the fixations at top and bottom.
- Design motion frequency, applicable dynamic soil properties, wave propagation
  in soil, and SSI effect.
- Nonlinearity of soil where it has a significant effect on design.

Therefore, a new simplified method was proposed for calculating the seismic earth
pressure [54]. A series of model walls were designed in the computer program
SASSI2000 to analyze the seismic effect of SSI on earth pressure. A typical model of this
wall is shown in Figure 2.11:

![Figure 2.11: Model Wall Created in SASSI2000 [54]](image)
In order to eliminate the rocking motion of the foundation, Ostadan [50] assumed a rock layer or firm soil under the base-mat. The infinite layers of soil were designed on the sides of the model with a specific shear wave velocity $V_s$, density $\rho$, material damping $\beta$, and Poisson’s ratio $\nu$. In addition, to collect data on the soil pressure on the wall, a column of soil was designed next to the model wall. In this model, vertically propagating shear waves were used as input motion with acceleration time history at the top of the rock layer.

Figure 2.12 shows the normalized transfer function for different shear velocities of backfill soil. Since the shape of the graph is the same for all different models and maximum amplification happens at the same frequency as the soil column, backfill soil can be assumed as a single degree of freedom (SDOF) whose dynamic response is defined by stiffness, damping and mass.

![Normalized Transfer Function](image)

**Figure 2.12: Normalized Transfer Function [54]**

Using these findings, Ostadan was able to find a simplified method to calculate the dynamic response of a non-yielding wall without sufficient movements to create an active wedge [55]. On the other hand, this method is able to consider the nonlinearity of soil in addition to the wave propagation effect of soil that has a significant influence on the
dynamic response. Figure 2.13 shows the comparison between M-O, Wood, and the proposed method:

![Figure 2.13: Comparison of Normalized Pressure Profile of Different Methods [54]](image)

Ostadan’s method includes a few simple steps. These steps can be summarized as follows:

1. Calculating the ground response at the depth corresponding to the wall’s base which can be done with the help of the computer program SHAKE [56].
2. Using Poisson’s ratio and density of soil to calculate total mass for an SDOF system by applying the equations below:

\[
\Psi_v = 2 / [(1-\nu)(2-\nu)]^{0.5} \tag{2.10}
\]

\[
m = 0.5 \rho \psi v \tag{2.11}
\]
3. Having ground response and mass calculated in previous steps, computing lateral seismic force and dividing this value by $0.744H$ to obtain the maximum lateral seismic soil pressure.

4. Multiplying peak pressure by pressure distribution (Eq. 2.12) to find the pressure profile.

$$P(y) = -0.0015 + 5.05y - 15.84y^2 + 28.25y^3 - 24.59y^4 + 8.14y^5$$ (2.12)

Experimental studies have been conducted using the same model [2, 3]. The Royal military college shaking table was used to apply a dynamic base excitation of the shape. The motion is a stepped-amplitude sinusoidal function at 5 Hz predominant frequency. A 5 Hz frequency (i.e., 0.2 s period) at 1/3 model scale corresponds to 2.5 Hz (i.e., 0.4 s period) at prototype scale according to the scaling laws [5]. Frequencies of 2 to 3 Hz are representative of typical predominant frequencies of medium to high frequency earthquakes [57], and fall within the expected earthquake parameters for most standards design [58, 59].

Results indicated that the horizontal earth pressure increased significantly above the static earth pressure due to base excitation [3]. In addition, the effect of input base acceleration on horizontal load is more pronounced at the top of the wall compared to the bottom. The top wall reaction increased 3 times the statically measured value compared to the bottom reaction which increased just 2 times the statically measured value.
Chapter 3: NUMERICAL MODELLING OF NON-YIELDING WALLS

3.1 Introduction

Numerical modelling methods are powerful techniques that have been used to study the static and dynamic behavior of non-yielding and rigid retaining walls [60, 61, 62, 63, 64, 65]. These techniques are recommended for the many advantages they have over conventional analytical methods. Such advantages include modelling of soil-structure interaction, different boundary conditions and configurations, and construction procedures. In addition, numerical models (i.e., finite element/difference) are able to give detailed information about stresses and strains in the soil, and structural deformations [57]. However, the accuracy of the results achieved by numerical modelling methods mainly depend on the correct choice of the material properties.

In order to achieve a high degree of confidence in the accuracy of the results obtained from numerical models, the responses predicted from numerical models need to be validated with the actual structure measured response. For this reason, the results of reduced-scaled model tests are used in this investigation to calibrate a numerical model [66]. The numerical model is developed to simulate the static and dynamic behavior of non-yielding retaining walls.

In this chapter, a description of the experimental models studied by El-Emam [3] is presented, followed by a very brief description of the program FLAC. Next, a detailed discussion of how the program was used to develop the non-yielding retaining wall model is introduced. The numerical results are compared with the response of the reduced-scale non-yielding model wall. Finally, the prototype dimensions and different parameters used in the parametric study are introduced and discussed.

3.2 Physical Model Non-Yielding Wall

The physical scaled model tests for non-yielding walls are used to verify the numerical model developed in the current study. The model height \(H\), width \(W\), and depth \(D\) were 1.0 m, 1.4 m, and 2.4 m, respectively [3]. A rigid strong box which was attached to the platform of the shaking table was used to hold the non-yielding retaining
wall and backfill soil. The criteria in designing the strong box container was to not
develop any active failure zones during maximum amplitude of input acceleration at the
far-end model wall. Therefore, the container was strengthened by steel beams and truss
frames at the back and front of the box. It was constructed so as to limit deformation at
the far-end model wall to 0.05 mm during 1g base acceleration. Since the floor of the
container was made of steel, a thin layer of the backfill sand was glued at the bottom of
the box to reduce the possibility of slippage between soil particles with steel floor of the
container. In order to reduce the effect of friction between the soil and the sidewalls of
the strong box, two layers of transparent polyethylene plus 6 mm-thick Perspex to cover
inside of the sidewalls was used. An example of a 1/4 scaled non-yielding model wall on
the shaking table platform is shown in Figure 3.1.

Figure 3.1: 1/4 Scaled Non-Yielding Model Wall on a Shaking Table Platform [3]
The type of sand used as retained soil was a uniformly graded sand with angular shape particles that was easy to compact. Values of the coefficient of curvature, $C_c$, and the coefficient of uniformity, $C_u$, were equal to 1.27 and 2.5, respectively. Different experiments were conducted prior to the real model to calculate the properties of the backfill soil [67]. These experiments showed that the value for maximum normal stress for a 1-meter-high model wall was equal to 15.7 kN/m$^2$ and the values for peak and residual friction angles were equal 51° and 46°, respectively. The soil properties are shown in Table 3.1 [3]. Figure 3.3 shows the grain size distribution curve for the sand.
Lateral earth force imposed on the wall was measured by load cells which were attached to the beam behind the top of the rigid non-yielding wall (Figure 3.4). This beam was used to hold the wall facing horizontally and to prevent the wall from both horizontal sliding and/or rotation. The model wall panel and instrumentation were designed so the researcher could record the horizontal and vertical loads developed at the toe of the wall [3]. This was done by using three linear roller bearings to support of wall panel with a base attached to the shaking table steel platform. Besides the fact that these three roller bearings reduce friction in the horizontal direction, they also can decouple the load exerted at the toe of the wall into horizontal and vertical components to be measured individually as shown in Figure 3.5. Cable-extension-position transducers, a type of
potentiometers, were used on the facing panel to record the deformation of the non-yielding retaining wall at the bottom, mid-height, and top of the model wall.

Figure 3.4: Wall Top Instrumentations

To construct the model with 1-m height, the volume change of the backfill soil due to vibratory compaction was controlled. This was done by constructing the backfill soil in many layers and compacting each layer before adding the next one. Researchers overcame this issue by dividing the backfill soil into 8 layers with 0.125 m thickness [3]. Vibration-induced compaction was applied for each layer. Constructing the model wall up to 1 m height was done by repeating the vibration process for each layer of backfill soil. At the end of the construction procedure, and in order to analyze the relation between repeated vibration and at-rest earth pressure for non-yielding retaining walls, the whole height of the backfill soil received two 5-second periods of vibration with a frequency of 6 Hz.
Table 3-2: Similitude Laws for 1-g Gravitational Field [5]

<table>
<thead>
<tr>
<th>Items</th>
<th>Scale Factors ((\lambda_d &amp; \lambda_p = 1)) (Prototype/Model)</th>
<th>Scale Factors ((\lambda = 4)) (Prototype/Model)</th>
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</thead>
<tbody>
<tr>
<td>Length (m)</td>
<td>(\lambda)</td>
<td>4</td>
</tr>
<tr>
<td>Density (kN/m(^3))</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Time (s)</td>
<td>((\lambda)^{0.5})</td>
<td>2</td>
</tr>
<tr>
<td>Stresses (kN/m(^2))</td>
<td>(\lambda)</td>
<td>4</td>
</tr>
<tr>
<td>Soil modulus (kN/m(^2))</td>
<td>(\lambda)</td>
<td>4</td>
</tr>
<tr>
<td>Displacement (kN/m(^2))</td>
<td>(\lambda)</td>
<td>4</td>
</tr>
<tr>
<td>Velocity (m/s)</td>
<td>((\lambda)^{0.5})</td>
<td>2</td>
</tr>
<tr>
<td>Acceleration (m(^2)/s)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Force (kN/m)</td>
<td>(\lambda^2)</td>
<td>16</td>
</tr>
<tr>
<td>Frequency (Hz)</td>
<td>(1/(\lambda)^{0.5})</td>
<td>0.5</td>
</tr>
<tr>
<td>Soil Strain</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Since the scale of the test model is 1/4 of the real non-yielding wall, all the parameters should be scaled down correctly to predict the behavior of the prototype quantitatively. Reduced-scale models are used as an economical option to study the behavior of the full-scale model. Therefore, the full-scale model should be scaled down correctly in order to get the accurate results. The scaling factors were found to be suitable for 1-g model tests. Table 3.2 illustrates the scaling factors [5, 2].
3.3 Numerical Model Development and Calibration

3.3.1 Dynamic Modeling Using FLAC

In order to develop the numerical model of a non-yielding retaining wall, the FLAC (Fast Lagrangian Analysis of Continua) program was used. FLAC [6] is a 2D stress analysis code, which is based on an explicit finite difference numerical method. This means the solution proceeds via a time stepping integration of Newton’s equation of motion for the various grid points in the system, even though a static solution of a problem is sought. The reason for including a dynamic equation of motion in the static solution is to ensure that the numerical scheme is stable when the physical system being modeled is unstable. One of the advantages of the explicit finite difference scheme in FLAC is that the global matrices are not formed, so there is no band width requirement. Therefore, the required memory is usually small and large displacements and strains are accommodated without additional computing effort. FLAC was used for detailed numerical analysis of the nonyielding model walls in this study as it provides the ability to:

- Model the large strain behavior and ongoing complex model walls’ behavior;
- Simulate changing loading conditions and material properties;
- Model the material behaviors in an acceptable and generally realistic manner, and;
- Simulate dynamic loading conditions such as earthquake loading.

Further benefits of using FLAC include:

- The solution method can handle the development of failure within the model without numerical difficulty.
- The nonlinear effect arising from material yield in shear or tension (material nonlinearity) can be treated, using various elasto-plastic constitutive models. The nonlinear response associated with large strains and deformation (geometric nonlinearity) can also be treated.

Figure 3.6 illustrates the calculation sequence programmed in FLAC.
The solution of a solid body in FLAC invokes the equations of motion and constitutive relations as well as boundary conditions. In its simplest form, the equation of motion relates the acceleration of a mass, $m$, to the applied force, $F$, which may vary with time. Figure 3.7 illustrates force acting on a mass, causing motion described in terms of acceleration, velocity, and displacement. Newton’s law of motion for the mass-spring system is:

$$m \frac{d \mathbf{u}}{dt} = F$$

(3.1)
In a continuous solid body, Equation 3.1 is generalized as follows:

\[ \rho \frac{\partial \mathbf{u}_i}{\partial t} = \frac{\partial \sigma_{ij}}{\partial x_j} + \rho \mathbf{g}_i \]  

(3.2)

Where

\[ \rho = \text{mass density}; \]
\[ t = \text{time}; \]
\[ x_i = \text{components of coordinate vector}; \]
\[ g_i = \text{components of gravitational acceleration (body forces); and} \]
\[ \sigma_{ij} = \text{components of stress tensor; and} \]
\[ i = \text{indices that denote the components in a Cartesian coordinate frame}. \]

The other set of equations applied to a solid, deformable body is the constitutive relation, or stress/strain law. In FLAC, the strain rate at each node is first derived from the velocity gradient as follows:

\[ \mathbf{e}_{ij} = \frac{1}{2} \left[ \frac{\partial \mathbf{u}_i}{\partial x_j} + \frac{\partial \mathbf{u}_j}{\partial x_i} \right] \]  

(3.3)

Where

\[ \mathbf{e}_{ij} = \text{strain-rate components; and} \]
\[ \mathbf{u}_i = \text{velocity components}. \]

Mechanical constitutive laws are of the form

\[ \sigma_{ij} := M(\sigma_{ij}, \mathbf{e}_{ij}, k) \]  

(3.4)

Where

\[ M(\ ) \] is the functional form of the constitutive law;
\[ k, \text{ depending on the particular, it is a history parameter(s) which may or may not be present} \]
\[ := \text{means “replaced by.”} \]
In general, nonlinear constitutive laws are written in incremental form because there is no unique relation between stress and strain. Equation 3.4 provides a new estimate for the stress tensor given the old stress tensor and the strain rate (or strain increment). The implementation steps of an elastic perfectly-plastic constitutive model with strain softening in FLAC can be found in the Itasca user manual [6].

Displacements are described in terms of prescribed velocities for each given gridpoint. In addition, Equation 3.2 is not invoked at the boundary gridpoints; instead, forces are derived at these points as follows:

\[ F_i = \sigma^b_{ij} n_j \Delta s \]  

(3.5)

Where \( n_i \) is the unit outward normal vector of the boundary segment, and \( \Delta s \) is the length of the boundary segment over which the stress \( \sigma^b_{ij} \) acts. The force \( F_i \) is added into the force sum for the appropriate gridpoint.

### 3.3.1 Numerical model dimensions and accuracy

Figure 3.8 shows the numerical grid of a nonyielding retaining wall developed in FLAC to simulate the behavior of model wall. To mimic the physical model test, the height and the backfill width of each model were chosen to be \( H = 1 \) m and \( D = 2.4 \) m [2, 3]. As prescribed in physical model tests, the thickness of the nonyielding retaining wall was considered as \( t = 76 \) mm. The right side of the model nonyielding wall was defined as a rigid boundary in order to behave the same as the rigid back wall of the container box in the physical model. Two-noded one-dimensional beam elements, with 3 hinges for each, were used to model the foundation boundary of the nonyielding retaining wall panel (Figure 3.8). This typical boundary condition at the foundation allows the wall to rotate, and at the same time facilitates the recording of the vertical and horizontal earth forces developed at the foundation. The nonyielding rigid panel wall, foundation, and far-end boundary were modelled using linear elastic zones with four nodes. The numerical grid for each model wall consisted of 1288 4-noded quadrilateral soil zones, 189 4-noded quadrilateral concrete zones representing the facing panel, a rigid far-end boundary and rigid concrete foundation, and 3 two-node one-dimensional beam elements simulating wall panel toe and top restraint boundary conditions. A sensitivity analysis was conducted in order to study the effect of numerical mesh refinement (i.e., number of
elements) on the model wall responses. A model finite deference mesh with the same dimensions was produced with different numbers of soil elements: 630, 820, and 1288. Examples of those different mesh refinements are shown in Figure 3.9. The numerical mesh size was selected so as to optimize the accuracy of results and at the same time optimize the computation time. A variation of model wall responses with the number of soil elements in numerical mesh is shown in Figure 3.10.

![FLAC Numerical Model of Non-Yielding Retaining Wall Sand Backfill](image)

**Figure 3.8:** FLAC Numerical Model of Non-Yielding Retaining Wall Sand Backfill

### 3.3.2 Material properties

The Mohr-Coulomb failure criterion was used to model the backfill soil on a non-yielding retaining wall. Elastic-plastic frictional material was used to address backfill soil. In addition, to study the pre-yield behavior of this material, constant values were chosen for the bulk and shear modulus. Table 3.1 represents the data collected from a direct shear test on the sand material [68]. FLAC was used to simulate the numerical model of the direct shear tests [4]. The main purpose of this simulation was to back calculate the peak plane strain friction angle of the soil. In addition, both shear and bulk modulus values were calculated using the same process. The peak plane strain friction angle from the shear box simulations was measured to be \( \phi_{ps} = 58^\circ \). This value was found to be consistent with the value predicted [69]. Table 3.3 presents a summary of the backfill soil properties that were used in this study.
The material parameters used for the non-yielding panel wall elements were a unit weight of $\gamma_w = 17.24 \text{kN/m}^3$, shear modulus $G_w = 1000 \text{Mpa}$, bulk modulus $K_w = 1100 \text{Mpa}$, and unlimited failure stress. The reason behind the selection of these values as bulk and shear modulus was to ensure that the facing of the non-yielding retaining wall was strongly rigid.

Figure 3.9: Numerical Model Meshed with Different Soil Element Numbers
Table 3-3: Properties of Backfill Soil Used in Numerical Parts [68]

<table>
<thead>
<tr>
<th>Soil property</th>
<th>Direct shear box test simulations using FLAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk unit weight (kN/m$^3$)</td>
<td>15.5</td>
</tr>
<tr>
<td>Peak friction angle</td>
<td>58°</td>
</tr>
<tr>
<td>Residual friction angle, $\phi_{cv}$</td>
<td>46°</td>
</tr>
<tr>
<td>Dilation angle, $\psi$</td>
<td>15°</td>
</tr>
<tr>
<td>Cohesion, $c$ (kPa)</td>
<td>0</td>
</tr>
<tr>
<td>Shear modulus (MPa)</td>
<td>7</td>
</tr>
<tr>
<td>Bulk modulus (MPa)</td>
<td>6</td>
</tr>
</tbody>
</table>

![Graph](image.png)

**Figure 3.10:** Effect of Number of Numerical Mesh Soil Elements on Model Wall Response

In order to model a non-yielding retaining wall in FLAC, two different interfaces are needed: (i) the interface between back-fill soil and the rigid foundation, and (ii) the interface between back-fill soil and the facing panel. The first interface between back-fill soil and the rigid foundation was defined as a thin (i.e. 0.02 m thickness) soil layer which had the same properties as the back-fill soil and was placed directly on the rigid foundation. This method was used by researchers to model the reinforced soil wall on a rigid foundation subjected to base acceleration [57]. The second interface between back-fill soil and the facing panel was modeled using a thin (i.e., 0.015 m thick) soil column with the same material properties of the back-fill soil and was placed directly behind the facing panel. Back-calculation of the friction angle between back-fill soil and the facing
column was done by measuring toe reactions and the sum of the measured connection loads in full-scale, using the equation below [70]:

$$\delta = \tan^{-1}\left(\frac{R_{yv} - W_f}{R_{Hv}}\right)$$  \hspace{1cm} (3.6)

Where $R_{yv}$ and $R_{Hv}$ are the measured vertical and horizontal components of the toe reaction, and $W_f$ is the weight of the facing panel. Sensors were attached at the toe of the retaining wall to record the horizontal and vertical force in the physical tests. Therefore, calculating the value of the interface friction angle can be done easily using Equation 3.6. An experiment to measure the value of the interface friction angle between steel and sand was conducted and proved that the maximum value of $\delta$ between soil particles and the steel box can reach a maximum of $2^\circ$ [71]. Therefore, for modelling the non-yielding retaining wall, the value of the internal friction angle was assumed to be equal to 2 degrees in order to reach numerical stability in FLAC.

### 3.3.3 Model wall construction stages simulation

To study the static compaction of a 2 m height non-yielding retaining wall, we used $K_o$ to reach the equilibrium condition [32]. The coefficient of at-rest lateral earth pressure, $K_o$ used in this analogy was calculated using Equation 2.3, with soil properties reported in Table 3.1. During construction of non-yielding model wall, the sand placement was constructed on 8 lifts with 0.125 m thickness. Each lift was compacted by shaking the model for 5 sec with 5 Hz base excitation [67]. The same steps were replicated with the construction of the numerical models. Each numerical model was constructed in 8 soil lifts. However, instead of shaking the model with a base excitation to compact the soil, a pre-defined initial stress $K_o$ was applied at each soil layer to compensate for compaction. This process was selected to reduce the time needed for numerical compaction using input base excitation. Therefore, each model was taken to equilibrium under $K_o$ stress condition before placing the next sand layer. Finally, the static response was measured by taking the model wall to static equilibrium before the wall responses were extracted and analyzed.
3.4 Over-Consolidation Ratio of Sandy Soil

A major goal in this study was to determine the change in the degree of consolidation of sandy soil due to compaction (i.e., vibratory compaction). To achieve this goal, the measured at-rest earth force was compared with the values theoretically calculated using Equation 2.3 with a different over-consolidation ratio (OCR). It should be noted that Equation 2.3 was used mainly to calculate the at-rest lateral earth pressure coefficient, $K_o$. However, the theoretical values of the at-rest lateral earth force, $P_o$, were calculated with the following expression for each height of backfill soil, $H_i$, in the construction stages:

$$P_o = \frac{1}{2} K_o \gamma H_i^2$$ (3.7)

In this equation, $\gamma$ is the unit weight of the backfill soil which is equal to 15.7 kN/m$^3$, and $K_o$ is the at-rest lateral earth pressure coefficient. The value of $K_o$ is calculated using Equation 2.6 with $\phi' = 58^\circ$. For normally-consolidated sand (i.e. $OCR = 1$), Equation 2.6 leads to similar results predicted using Jaky’s formula (i.e., Equation 2.3). Figure 3.12 illustrates the calculated theoretical values of at-rest lateral earth pressure at different backfill heights and over-consolidation ratios. In addition, the values of lateral earth force for each backfill height in the construction stage were measured from top and bottom loads (Figure 3.11b). The values of the at-rest earth lateral force, $R_{Hi}$ were also plotted in Figure 3.12. It should be noted that the horizontal force measured at the top and bottom of the panel wall at different construction stages, $R_{Hi}$ is equivalent in magnitude and opposite in direction to the at-rest lateral earth pressure force $P_{El}$ (Figure 3.11b), developed at the back of the panel wall. The trendline of the measured values of at-rest lateral earth force with different backfill heights is very close to the calculated theoretical at-rest lateral earth forces trend. Furthermore, the measured values of at-rest lateral earth force are much closer to the theoretically-calculated values of lateral earth force for sandy soil with $OCR = 4$ at different heights of construction stage. This agreement between measured and theoretical values of lateral earth force increased as the backfill height became larger than 0.4 m, which is attributed to the greater density of sand with larger heights. Results reported in Figure 3.12 clearly show that Equation 2.6 can be used to
predict the values of the at-rest lateral earth pressure coefficient for over-consolidated sand [19]. Finally, Equation 2.6 can be used in conjugate with carefully-conducted experimental tests to relate the variation of sand over-consolidation ratio to the compaction effort.

a) Full-Height Wall (Prototype) \hspace{1cm} b) Construction Stages (Model)

**Figure 3.11:** Typical Force Diagram Used for Analysis of the Numerical Model

**Figure 3.12:** Variation of Horizontal Earth Force with Backfill Height During Construction Stages at Different Over-Consolidation Ratios
3.5 Comparison between Predictions and Test Measurements

The measured values of lateral earth force, vertical earth force, and the location of the lateral earth force resultant, at different construction stages (i.e., different backfill heights $H_i$), were used to calibrate the numerical model developed in FLAC. Figure 3.13 shows both measured and predicted values of lateral earth force ($R_{Hi}$), vertical earth force ($R_{Vi}$) mobilised at the footing of the wall panel, and the lateral earth force resultant elevation above the wall footing ($v_i$) normalized to the backfill height. It should be noted that $R_{Hi}$ is the summation of the bottom horizontal reaction $R_{HBI}$ and the top horizontal reaction $R_{HTI}$ (see Figure 3.12 for these responses). Those responses are measured in the physical model and predicted in the numerical model at different backfill heights, $H_i$ (i.e., during the construction stages). Plotted also in Figure 3.13 are the theoretically-predicted values of the measured responses. The theoretical earth force plotted in Figure 3.13a is calculated using Equations 2.6 and 3.7 with $OCR = 4$. The at-rest earth pressure theory usually assumes zero relative movement between the wall and the backfill soil. Therefore, a zero value of vertical earth pressure at the back of the wall panel is usually assumed, and only the weight of the facing panel ($W_f$) is considered as the vertical force acting at the wall footing (Figure 3.13b). The theoretical resultant elevation ($v_i$) shown in Figure 3.13c is taken as $H/3$ as usually assumed by the earth pressure theories. After placement and compaction of each layer of backfill soil, horizontal and vertical earth force values were collected. In addition, the location of the lateral earth force was calculated. Each measured response value was presented as a point in Figure 3.13. However, the numerical results showed both stages for each soil lift.
Figure 3.13: Predicted and Measured Lateral Earth Force, Vertical Earth Force, and Normalized Resultant Elevation

Figure 3.13 proves very good agreement between FLAC calculated total wall forces and the experimental results, both qualitatively and quantitatively. Figure 3.13b illustrates the measured and predicted values of vertical earth force on the non-yielding wall. It
proves that both of these values are very close to the wall facing’s own weight, $W_f$. This is a clear support of the near-zero vertical earth force assumption adopted by the at-rest earth pressure theory.

For backfill heights larger than 0.5 m, both numerical and experimental values of the location of the resultant lateral earth force are close to each other (Figure 3.13c). However, it shows that for backfill soil heights less than 0.5 m, the numerical model under-predicts the location of the lateral earth force resultant which may be the result of having a perfect bond between the foundation and the backfill soil. It should be noted that the at-rest earth pressure theory under-predicts the location of the resultant force to be at 0.33H according to both numerical and experimental results. This bottom boundary effect appears diminish as the backfill height increases above the foundation level.

### 3.6 Prototype Wall Dimensions and Material Properties

The geometry and configuration of the reference non-yielding wall used in the parametric study is shown in Figure 3.14. The geometrical dimensions are equal to the dimensions of the 1/4 scaled numerical model, developed and calibrated, and multiplied by the scaling factors with $\lambda = 4$ [2, 3, 5]. The following are the general boundary conditions and design factors of the model walls analyzed in the current parametric study:

- All model walls are constructed on a firm foundation, and the bearing capacity failure of the foundation soil is not a concern in this study.
- All model walls are constructed with a vertical full-height rigid panel.
- In all model walls, the backfill surface is horizontal (i.e. $\beta = 0$).
- The retained backfill is assumed to be dry cohesionless soil (i.e. $c = 0$).

The material properties for the 1/4-scale model wall and the equivalent 4 m-high prototype wall (Figure 3.14) are shown in Table 3.4. The material properties for the prototype were calculated using the properties from the reduced-scale models and similitude laws with $\lambda = 4$ (where $\lambda$ is the length scale factor) [5]. The FLAC numerical grid for the simulation of the prototype non-yielding wall is similar to the numerical grid developed for the 1/4 scale model multiplied by a length scale factor of $\lambda = 4$. The height, $H$, and the width, $D$, of each prototype wall were kept at 4 m and 10 m, respectively. The
foundation in the numerical model of the prototype wall was assumed to be rigid concrete with a thickness of \( t = 600 \text{ mm} \), which simulated the rigid platform of the containing box. The thickness of the non-yielding wall was 300 mm to match the prototype wall (Figure 3.14). In addition, the unit weight of the non-yielding wall was equal to \( \gamma_w = 17.24 \text{ kN/m}^3 \) and the material properties were chosen to be linear elastic with unlimited failure stress. Also, the value of the bulk modulus, \( K_w \) and the shear modulus were taken to be equal to 4400 and 4000 Mpa, respectively. These specific values of the shear and bulk modulus were back-calculated from the calibrated model wall and the similitude rule [5]. Each model wall was constructed in 8 soil layers, and was taken to static equilibrium after the placement of each soil layer. Upon completing its construction, the model wall was taken to static equilibrium to determine the wall static responses. Figure 3.15 shows the numerical mesh and dimensions for the prototype model.

![Figure 3.14: Reference Geometry and Configuration for the Prototype Wall](image)

**Figure 3.15:** FLAC Numerical Model of Non-Yielding Wall at Prototype Scale Retaining Sand Backfill

**Table 3-4:** Control Case Material Properties for Scale Model and Prototype Walls Used in Parametric Study

<table>
<thead>
<tr>
<th>Input Property</th>
<th>Model (H&lt;sub&gt;m&lt;/sub&gt; = 1 m)</th>
<th>Prototype (H&lt;sub&gt;p&lt;/sub&gt; = 4 m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak friction angle, φ&lt;sub&gt;Ps&lt;/sub&gt; (deg.)</td>
<td>58</td>
<td>58</td>
</tr>
<tr>
<td>Residual friction angle, φ&lt;sub&gt;Res&lt;/sub&gt; (deg.)</td>
<td>46</td>
<td>46</td>
</tr>
<tr>
<td>Cohesion, c (MPa)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Dilation angle, ψ (degrees)</td>
<td>14.5</td>
<td>14.5</td>
</tr>
<tr>
<td>Density (dense state), γ (kN/m&lt;sup&gt;3&lt;/sup&gt;)</td>
<td>15.7</td>
<td>15.7</td>
</tr>
<tr>
<td>Shear Modulus, G (MPa)</td>
<td>7.0</td>
<td>28</td>
</tr>
<tr>
<td>Bulk Modulus, K (MPa)</td>
<td>6.0</td>
<td>24</td>
</tr>
</tbody>
</table>

*H<sub>m</sub> and H<sub>p</sub> are the model and prototype wall heights, respectively.*
3.7 Conclusions

This chapter describes the numerical model developed by El-Emam [3]. A detailed description of the numerical model was also presented. The numerical simulations were carried out using the commercially available dynamic finite difference program FLAC [4]. The numerical model walls were constructed in the same way and procedures followed in the experimental model. The numerical model was able to capture the trend in the experimental data and in most cases gave reasonably accurate estimates of the magnitude of all measured wall responses ($R_{Hb}$, $R_{Vi}$, and $y_i$). The numerical results confirmed the zero interface friction angle at the back of the wall. The calibrated model was used together with Iai [7] similitude to develop a prototype wall with 4 m height. The prototype wall is used in the next chapters to conduct a parametric study in order to investigate the static and dynamic responses of non-yielding walls under different design parameters. The results of this parametric study are presented in Chapters 4 and 5.
Chapter 4: STATIC RESPONSES OF NON-YIELDING RETAINING WALLS

4.1 Introduction

The parameters of non-yielding walls examined in this study are divided into two categories. The first category includes the material properties of the wall-soil system such as backfill soil friction angle ($\phi$), wall panel elasticity ($E_s$), degree of consolidation of sand backfill ($OCR$), and wall-soil interface friction angle ($\delta$). The second category includes the geometrical properties of the wall such as the retaining wall height ($H$) and the wall inclination ($\omega$). In this section, the effect of each of these parameters on the static model wall response is presented and discussed.

![Typical Force Diagram Used for Analysis of the Numerical Model](image)

**Figure 4.1:** Typical Force Diagram Used for Analysis of the Numerical Model [2]

Magnitude and locations of forces used for the analysis of the wall response are shown in Figure 4.1. For each model wall, both top and bottom vertical loads, $R_{VT}$ and $R_{VB}$, are directly recorded during the numerical analysis. In addition the top and the bottom horizontal loads, $R_{HB}$ and $R_{HT}$ are also recorded. The total lateral earth force, $R_H$,
the total vertical force, \( R_V \), and the earth pressure resultant location above the base, \( y_R \) are calculated as:

\[
R_H = R_{HB} + R_{HT}
\]  
(4.1)

\[
R_V = R_{VB} + R_{VT}
\]  
(4.2)

\[
y_R = R_{HT} / R_H
\]  
(4.3)

### 4.2 Effect of Backfill Soil Friction Angle (\( \phi \))

To study the effect of the backfill soil friction angle (\( \phi \)) on the static response of the non-yielding wall, five different granular soils were chosen as the backfill material. The values of soil friction angle (\( \phi \)) ranged from 30\(^\circ\) to 50\(^\circ\) with 5\(^\circ\) increments, which represents the full range of sandy soil friction angles. The variations in wall lateral deflection at different heights with the backfill soil friction angle is shown in Figure 4.2. As expected, increasing the backfill soil friction angle increased the resistance of the soil to shearing; therefore, wall deflection was decreased (Figure 4.2a). An increase in the friction angle from 30\(^\circ\) to 35\(^\circ\) (i.e., a 5\(^\circ\) increment) reduced the lateral displacement of the wall by about 4.7%; however, an increase in the friction angle from 45\(^\circ\) to 50\(^\circ\) reduced the wall lateral displacement by 18.5%. Therefore, the effect of increasing the soil friction angle in reducing the wall lateral displacement diminished at relatively lower values of soil friction angle.

Figure 4.2b illustrates the relationship between earth pressure distributions for different values of backfill soil friction angle. In addition, this figure shows the theoretical lateral earth pressure distribution obtained from Jaky’s equation and the Mayne and Kulhawy formula for \( OCR = 1 \) and \( OCR = 4 \), respectively (Eqs. 2.3 and 2.6) [13, 19]. As can be seen, the lateral earth pressure distribution for smaller values of friction angle (i.e. \( \phi = 35^\circ \)) has almost a triangular shape. As the backfill friction angle increases above 35\(^\circ\), the distribution becomes significantly deviated from the hydrostatic type. Figure 4.2b indicates the huge difference between the numerical lateral earth pressure and the predicted theoretical values from Jaky’s formula for \( OCR = 1 \) (Eq. 2.3). This huge gap is due to the over-compaction of backfill soil (\( OCR > 1 \)) which results in
higher values of earth pressure near the backfill’s surface compared to the bottom of the wall. These results are in good agreement with the experimental results of [40], which showed higher earth pressure at the top of the vibratory compacted sand than the bottom. Therefore, the lateral earth pressure distribution exerted on the non-yielding model wall deviates significantly from both the hydrostatic type and the traditional Jaky’s formula [4].

**Figure 4.2:** Effect of Backfill Soil Friction Angle on Wall Lateral Deflection and Earth Pressure

Figure 4.3 shows the variation of external forces (i.e., $R_H$ and $R_V$) developed at the back of the wall, with the backfill soil friction angle ($\phi$). As expected, increasing the soil friction angle (i.e., larger soil shear resistance) considerably decreases external horizontal forces ($R_H$) within the model wall (Figure 4.3a). This is an indication that the total earth forces at the back of the facing panel, $P_E$, decreased significantly with an increasing soil
friction angle. For the values of friction angle used in this study, Equations 2.3 and 2.6 significantly under-predicted the magnitudes of the total horizontal earth force, $R_H$ (Figure 4.2a). Jaky’s formula is shown to under-predict the lateral earth force $R_H$ by about 65% at $\phi = 50^\circ$, increased to 72% at $\phi = 30^\circ$. However, the Mayne and Kulhawy formula under-predicts the lateral earth force $R_H$ only by about 20% at $\phi = 50^\circ$, increased to 30% at $\phi = 30^\circ$. This is a clear indication that the Mayne and Kulhawy formula is closer to reality compared to the outdated Jaky’s equation.
Figure 4.3: Variation of Vertical and Horizontal Forces with Backfill Soil Friction Angle ($\phi$)

Figure 4.3b illustrates that the variation of the soil friction angle slightly changes the vertical load developed at the base, $R_V$. In addition, the figure indicates that the value of the vertical load predicted at the base of the wall $R_V$ is about 35% more than the self-weight of the wall, $W_w$ for different values of friction angle used in this study. Therefore,
Jaky’s formula under-estimated the magnitude of the vertical toe loads by about 35% at different values of friction angle used in this study. This is attributed to the down-drag force developed between the backfill soil and the back of the wall due to wall lateral deflection.

Figure 4.4 shows the numerically-measured and theoretically-predicted resultant elevation ($y_R$) above the wall footing. As the backfill soil friction angle increased, the earth pressure distribution drifted towards the top of the wall (Figure 4.2b). Therefore, the earth pressure resultant location was also dragged towards the top of the wall as indicated in Figure 4.4. It is clear from the figure that the location of the resultant lateral earth forces above the footing of the wall increased as the soil friction angle increased. In addition, for all values of friction angles used in this study, the numerically-predicted location of the lateral earth force ($y_R$) is higher than the $H/3$ value assumed by [13, 19].

![Figure 4.4: Effect of Backfill Soil Friction Angle on the Location of the Earth Force Resultant](image-url)
4.3 Effect of Backfill Soil Degree of Consolidation (OCR)

The effect of backfill soil degree of consolidation (OCR) on the wall lateral earth pressure are shown in Figures 4.5 ($\phi = 30^\circ$ and $40^\circ$) and 4.6a ($\phi = 50^\circ$). Four different values of degree of consolidation have been used ($OCR = 1, 2, 3, \text{ and } 4$). Sand fills are usually normally consolidated prior to compaction with $OCR = 1$. Investigations have shown that subsequent compaction of laterally constrained sand results in a significant increase in the degree of consolidation and horizontal stress in soil [35, 36, 37, 38]. The over-consolidation ratio of sand is defined as the ratio of the maximum effective vertical stress ($\sigma'_{v-max}$) to the current effective vertical stress ($\sigma'_{v-current}$).

Figure 4.5: Effect of Backfill Soil Degree of Consolidation on Wall Lateral Earth Pressure for ($\phi = 30^\circ$ and $40^\circ$)

Results shown in Figures 4.5 and 4.6a indicate that, for the different friction angles ($\phi$) used in the current study, as the values of the over-consolidation ratio (OCR) increase,
the earth pressure values at different wall heights also increase. In addition, the variation of the lateral earth pressure distribution with depth tends to be closer to a triangular shape for friction angles of $30^\circ$. For friction angles higher than $30^\circ$ the earth pressure distribution deviates from the triangular shape towards a near rectangular shape, especially for the bottom $\frac{3}{4}H$. However, the distribution is always triangular in shape regardless of the value of the OCR and friction angle for the top $\frac{1}{4}H$. It can be noticed that, for friction angles larger than $30^\circ$, the earth pressure in the middle half of the wall height reduces slightly as a result of the larger wall deflection in this region (Figure 4.6b).

![Figure 4.6: Effect of Backfill Soil Degree of Consolidation on Wall Lateral Earth Pressure and Deflection for ($\phi = 50^\circ$)](image)

Figures 4.5 and 4.6a also indicate that the numerically-predicted earth pressure distributions increase beyond the theoretical distribution assumed by Jaky [4] when the degree of consolidation of sand increases beyond the normally consolidated status. This
result is in agreement with Mayne and Kulhawy [18] who reported that the theoretical
distribution assumed by Jaky is closer to the numerically predicted value when $OCR = 1$.

The variation of wall lateral deflection versus wall height at different backfill soil
degrees of consolidation is shown in Figure 4.6b. As expected, increasing the backfill soil
over-consolidation ratio increased the lateral stress applied on the wall (Figure 4.6a) and
as a result increased the wall lateral deflection. This is a clear indication that over-
compaction of sandy soil in the vicinity of the non-yielding wall produces a significant
increase of lateral wall lateral deflection compared to lightly compacted sand.

The variation of horizontal earth forces ($R_{H}$) developed at the back of the wall, with
the backfill degree of consolidation, is shown in Figure 4.7a. It is clear that, for all values
of backfill soil friction angle used in the study, the horizontal earth forces ($R_{H}$) imposed
on the non-yielding wall significantly increase with the backfill soil degree of
consolidation. In addition, the theoretically-predicted values of $R_{H}$ are in close agreement
with the numerically-predicted values for normally consolidated sand (i.e., at $OCR = 1$).
This result is compatible with the findings of [20] who concluded that Jaky’s formula is
practically accepted for normally consolidated soil. For over-consolidated sand (i.e., $OCR
> 1$) the theoretical equation proposed by Mayne and Kulhawy under-predicts the lateral
earth force developed on the non-yielding wall. The difference between the numerical
and theoretical values of the lateral earth force increases as the degree of consolidation
increases and as the soil friction angle decreases. It should be noted that the largest
difference between the theoretically- and numerically-predicted lateral earth forces is
attained at a backfill soil friction angle $\phi = 30^\circ$, and at a degree of consolidation ratio,
$OCR$, equal to 3 to 4. Finally, it appears from Figure 4.7a that the effect of the over-
consolidation ratio on the lateral earth force starts to diminish at $OCR > 4$ for backfill soil
with a friction angle $\phi = 30^\circ$. If this observation is extrapolated for higher friction angles
(i.e., $\phi = 40^\circ$ and $50^\circ$), it is expected that the effect of the over-consolidation ratio on
lateral earth forces will be diminish at $OCR > 4$.

Figure 4.7b shows the variation of the vertical earth force developed at the base of the
wall ($R_{V}$) at different over-consolidation ratios. It can be seen that the magnitudes of the
predicted vertical load ($R_{V}$) are generally larger than the self-weight of the wall panel
($W_w$) for both normally-consolidated and over-consolidated sand. This result indicates
that the wall back is not perfectly smooth and a down-drag force is developed between the backfill soil and the wall. This down-drag force is slightly affected by the backfill soil degree of consolidation.

**Figure 4.7:** Effect of Backfill Soil Degree of Over-Consolidation and Friction Angle on Both Vertical and Horizontal Force Resultant
A close look at Figure 4.7b confirms that the vertical load developed at the foundation of the non-yielding wall could be 30% to 60% larger than the self-weight of the wall, depending on the backfill soil degree of consolidation and soil friction angle. Neglecting this additional force during foundation design may result in a non-conservative foundation. It should be clearly mentioned that the coefficient of friction ($\tan\delta$) between the backfill soil and the wall was kept constant for all numerical models except when the effect of this parameter needed to be investigated (Section 4.5).

![Figure 4.8: Effect of Backfill Soil Degree of Consolidation on the Location of the Horizontal Earth Force Resultant](image)

Numerically-predicted values of horizontal earth force resultant elevation ($y_R$) above the wall footing is shown in Figure 4.8 for different backfill soil degrees of consolidation and different soil friction angles. Shown also in Figure 4.8 are the theoretical values of the earth force location assumed by Jaky for normally-consolidated soil and by Mayne and Kulhawy for over-consolidated soil. It should be mentioned that both methods adopted the triangular distribution for earth pressure with the earth pressure resultant located at $H/3$. Numerical results in Figure 4.8 indicated that the location of the resultant
lateral earth force above the wall footing is well above the theoretically assumed $H/3$ (i.e. $y_R > 0.33H$). This conclusion is true for all backfill soil friction angles and degree of consolidation used in the current study. The resultant force moves slightly downward when the backfill soil degree of consolidation increases and the friction angle decreases. In conclusion, for all values of over consolidation ratios and friction angles used in this study, the resultant earth force is located at or slightly below the wall mid-height (i.e. $y_R \approx 0.4H$ to $0.5H$).

**4.4 Effect of model wall elasticity ($E_S$)**

Different mixtures produce concrete with different compressive strengths, which in turn produce a different elastic modulus, $E_S$. The effect of the wall elastic modulus on both lateral deflection and lateral earth pressure is shown in Figure 4.9. Four different values of wall elastic modulus have been used in this study ($E_S = 2.1, 21, 34,$ and 47 GPa). The last three values of elastic modulus (i.e., $E_S = 21, 34$ and 47 GPa) represent walls constructed with low, medium, and high strength concrete, respectively. The lowest value of elastic modulus ($E_S = 2.1$ GPa) represents walls constructed with wooden material for braced excavation. Variations of wall lateral deflection at different heights with the wall elastic modulus ($E_S$) are shown in Figure 4.9a. As expected, the wooden material wall shows a lateral deflection about 3 to 4 times higher than that of the low strength concrete material wall. This large deflection reflected on the lateral earth pressure developed at the back of the wall is shown to be significantly less compared to the concrete wall (Figure 4.9b). It is well understood that as the wall lateral deflection increases, the backfill-soil-mobilized shear strength and the lateral earth pressure decrease.

For the walls constructed with different concrete materials, the reduction of lateral deflection was 22% if the wall was constructed with medium strength concrete instead of low strength concrete. However, constructing the wall with high strength concrete resulted in a 13% reduction in lateral deflection compared to the medium strength concrete wall. This difference in lateral deflection due to different concrete mixtures was slightly reflected on the lateral earth pressure developed at the back of the wall (Figure 4.9b). Earth pressure distributions showed in Figure 4.9b indicated that the concrete...
strength slightly affected the lateral earth pressure distribution at the back of non-yielding walls. Finally, for the range of elastic modulus used in the current study, the theoretical distribution assumed by Jaky is far below the numerically-predicted distribution. This is an expected result as the over-consolidation ratio for all four model walls is $OCR = 4$.

![Figure 4.9: Effect of Wall Modulus of Elasticity on Wall Lateral Deflection and Earth Pressure](image)

The effects of the wall elastic modulus, $E_s$, on the horizontal and vertical resultant forces, $R_H$ and $R_V$, are shown in Figure 4.10. As this figure indicates, using concrete retaining walls resulted in a 33% increase in the horizontal earth force, $R_H$, compared to wooden constructed non-yielding walls. However, the vertical resultant forces, $R_V$, showed very slight changes using walls with different elastic modules. For the three walls constructed with concrete facing, increasing the elastic modulus of the concrete showed a slight increase in the horizontal earth force, $R_H$. Results shown in Figure 4.10 also indicate that the resultant horizontal earth forces at the back of the facing panel, $R_H$, are
larger than the theoretically-predicted values for all values of $E_s$ used in the current study. However, the values of lateral earth force predicted by Mayne and Kulhawy are closer to the numerical values. Similarly, the magnitudes of the vertical load, $R_V$, predicted numerically were generally larger than the self-weight of the facing panel, $W_W$, for all values of $E_s$. This indicates that a down-drag force is developed between the backfill soil and the wall, and this down-drag force is not affected by the wall elastic modulus, $E_s$.

![Figure 4.10: Effect of Wall Modulus of Elasticity on Vertical and Horizontal Forces](image)

**Figure 4.10:** Effect of Wall Modulus of Elasticity on Vertical and Horizontal Forces

Numerically- and theoretically-predicted values of resultant elevation ($y_R$) above the wall footing are shown in Figure 4.11 for different wall elastic modulus, $E_s$. The figure indicates that, for all values of wall elastic modulus $E_s$, the elevation of the resultant lateral earth force above the wall footing is well above the theoretically assumed $H/3$ value assumed earlier. For non-yielding walls constructed with wood material, the earth pressure resultant is located approximately at mid-height (i.e., $y_R = 0.5H$). However, for walls constructed with concrete material, the earth pressure resultant is located slightly below the wall’s mid-height, at approximately $y_R = 0.45H$. In conclusion, for walls
constructed with concrete material, the elastic modulus slightly affected the location of the resultant lateral earth force, $y_R$. 

![Graph showing the effect of wall modulus of elasticity on location of earth force resultant](image)

**Figure 4.11**: Effect of Wall Modulus of Elasticity on Location of Earth Force Resultant

### 4.5 Effect of Wall-Soil Interface Friction Angle ($\delta$)

The interface between the non-yielding wall and the backfill soil was modeled in the current study using a thin soil column with 0.06 m thickness inserted between the wall and the backfill soil. This method has been successfully used to model the interface between facing panel and backfill soil in reinforced soil walls [72]. The reasons for using this method over real interface modeling are its simplicity and straightforward determination of the interface parameters. In addition, the execution of the model is faster and more stable with dynamic analysis compared to the real interface [67]. The soil column in this analysis is given similar backfill soil properties except for the angle of internal friction, $\phi$. In all reference models studied, the friction angle was assumed to be very small (i.e. $\delta = 2^\circ$), which was compatible with the experimental model tested by [2, 3]. In this section, to study the effect of the wall panel friction angle, $\delta$, on the response of
a non-yielding retaining wall, three different values of $\delta$ were used (i.e., $\delta = 0.3\phi$, $0.4\phi$, and $0.6\phi$).

Variations of wall lateral deflection at different heights with the wall friction angle, $\delta$, are shown in Figure 4.12. As expected, increasing the wall-soil interface friction angle slightly decreases the lateral displacement of the non-yielding retaining wall. The difference of lateral deflection between the wall with highest ($\delta = 0.6\phi$) and lowest ($\delta = 2^\circ$) values of wall-soil interface friction angles is less than 10%, which is considered insignificant.

![Figure 4.12: Effect of Wall-Backfill Soil Interface Friction Angle, $\delta$, on Wall Lateral Deflection and Lateral Earth Pressure](image)

Earth pressure distributions on the back of the wall at different wall-soil interface friction angles, $\delta$, are shown in Figure 4.12b. Also shown in this figure are the theoretical
at-rest earth pressure distributions. The maximum effect of $\delta$ on the earth pressure occurred at 0.25H from the top of the wall. At this location, a 22% reduction in the lateral earth pressure occurred due to a change from a perfectly smooth wall-soil interface (i.e., $\delta = 2^\circ$) to a rough interface (i.e., $\delta = 0.6\phi$). The effect of the interface friction angle, $\delta$, became insignificant for the top 0.25H and the bottom 0.5H. It can be concluded that the interface friction angle only affects the maximum lateral earth pressure value, which occurred at 0.25H from the top of the wall. Finally, the earth pressure distribution by Jaky and Mayne and Kulhawy do not follow the numerical results and cannot consider the effect of the interface friction angle.

![Figure 4.13: Effect of Wall-Backfill Soil Interface Friction Angle, $\delta$, on Vertical and Horizontal Earth Forces](image)

Variations of horizontal and vertical earth forces ($R_H$ and $R_V$) with different facing panel roughness are shown in Figure 4.13. It is clear that the interface friction angle between the wall and the backfill soil has an insignificant effect on the lateral earth pressure forces developed at the back of the wall. It is well known that relative movement is a major factor for the friction to come into effect between any two contact objects. This
is expected, as the movement of a non-yielding wall is very limited and not enough to develop relative movement between the wall and the backfill soil. On the contrary, increasing the roughness of the wall panel results in a significant increase in the vertical earth force, $R_V$. This is due to the down-drag force developed between the backfill soil and the back of the wall. According to Figure 4.13, a change from a perfectly smooth facing/soil interface (i.e. $\delta = 2^\circ$) to a rough interface (i.e. $\delta = 0.6\phi = 35^\circ$) results in a 130% increase in magnitude of vertical earth force developed at the back of the wall. This vertical force is almost 2.5 times the wall self-weight $W_W$, and is not considered by the current design methods. Neglecting this significant vertical force at the wall foundation is non-conservative.

Figure 4.14 shows both the numerically-measured and theoretically-predicted resultant elevations ($y_R$) above the wall footing normalized to the wall height, $H$. As mentioned before, the wall surface roughness showed an insignificant effect on the value of lateral earth pressure and distribution at the back of the wall (Figure 4.12b). Therefore, the resultant horizontal earth force (Figure 4.13) and its location above the base (Figure 4.14) were insignificantly affected by the interface friction angle, $\delta$. It is clear from Figure 4.14 that the resultant earth force is located at approximately $0.5H$ regardless of the interface friction angle value. In addition, the numerically measured earth force location was well above the $0.33H$ assumed by Jaky and Mayne and Kulhawy, which seems to underestimate the location of the lateral earth force.
4.6 Effect of Wall Inclination ($\omega$)

To study the effect of model wall inclination on the behavior of a non-yielding retaining wall, three different inclination angles were chosen ($\omega = 5^\circ$, $10^\circ$, and $15^\circ$) and the results were compared to the reference vertical model wall (i.e., $\omega = 0^\circ$ with the vertical). Figure 4.15 shows the numerical grids for the model wall with different inclination angles, $\omega$. Figure 4.16 shows the effect of the wall inclination angle, $\omega$, on the lateral displacement and lateral earth pressure distribution at the back of the wall. Results shown in Figure 4.16b indicate that wall inclination angles equal to $5^\circ$, $10^\circ$ and $15^\circ$ from the vertical result in $9\%$, $18\%$ and $27\%$ reductions in the maximum mid-height lateral deflection of the wall, respectively, compared to the vertical-facing panel (i.e., $\omega = 0^\circ$). The amount of reduction in the lateral deflection per degree of facing panel inclination angle seems to be constant at all values of inclination angle used in this study. This means a linear relation can be derived between the reduction in lateral deflection and the wall inclination angle.
Variations of lateral earth pressure applied on the back of the wall at different inclination angles of the non-yielding retaining wall are shown in Figure 4.16b. This figure proves that although the trend line is the same for all different inclination angles, increasing the inclination angle of the non-yielding retaining wall results in a slight decrease on the lateral earth pressure exerted on the back of the wall. The effect of the wall inclination angle on the lateral earth pressure is more pronounced at the middle half of the wall (i.e., from $0.25H$ to $0.75H$). For the top and bottom quarter of the wall height, the effect of the wall inclination on the lateral earth pressure is insignificant. Finally, the earth pressure distribution predicted by Mayne and Kulhawy is closer to the numerical distributions compared to the values predicted by Jaky.
Figure 4.16: Effect of Wall Inclination Angle, $\omega$, on Wall Lateral Deflection and Lateral Earth Pressure

The effect of the wall inclination angle on both the horizontal and vertical earth forces is shown in Figure 4.17. It is clear from the figure that increasing the wall inclination angle results in a significant decrease in both vertical and horizontal earth forces developed at the back of the wall. A facing inclination angle of 5 degrees ($\omega = 5^\circ$) led to a 13% and 18% reduction of the total horizontal and vertical earth forces behind the inclined facing compared to vertical facing wall, respectively. Figure 4.17 indicates that there are linear relationships between the wall inclination angle and the reduction in both vertical and horizontal earth forces. This figure illustrates that the current design methods cannot capture the trend of the effect of the facing panel inclination angle on the vertical and horizontal earth forces. In addition, the calculated values of horizontal earth force became equal and less than the predicted values by Mayne and Kulhawy as the facing
inclination angle increased. In all values of the facing inclination angle, Jaky’s equation neither captures the magnitude nor the trend of the horizontal earth force. It should be noted that the value of the vertical earth force decreased to a value lower than the self-weight of the wall, $W_W$. This is logical as the backfill under the wall horizontal projection participated with the wall foundation in carrying the vertical force.

![Diagram showing normalized force vs. wall inclination angle]

**Figure 4.17:** Effect of Wall Inclination Angle, $\omega$, on Vertical and Horizontal Earth Forces

The numerically- and theoretically-predicted values of normalized resultant elevation ($y_R$) above the wall footing are shown in Figure 4.18 for different wall inclination angles. The figure indicates that the horizontal earth force resultant elevation above the base of the wall, $y_R$, slightly decreased as the wall inclination angle increased. However, the numerically-calculated value of $y_R$ is well above the theoretically assumed values (i.e. $y_R = H/3$). In conclusion, a slight inclination of the non-yielding wall towards the backfill soil reduces both vertical and horizontal earth forces, as well as the resultant elevation above the wall base.
4.7 Model Walls with Different Heights ($H$)

Figure 4.19 plots the wall lateral deflection normalized to the wall height, $H$, and the lateral earth pressure normalized to $\gamma H$, for walls with different heights. Four different values of wall height have been tested numerically (i.e., $H = 4, 6, 8, \text{ and } 10 \text{ m}$). Figure 4.19a shows that the normalized wall lateral deflection increased significantly with the wall height. An increase of wall height from 4 to 6 m (i.e., a 2 m increase) increased the lateral displacement of the wall by about 60%; however, an increase in the model wall height from 6 m to 8 m (i.e., a 2 m increase) increased the wall lateral displacement by 38%. An additional 2 m increase in the wall height from 8 m to 10 m resulted in an increase in the normalized wall lateral deflection by about 29%. Therefore, the effect of increasing the model wall height in the wall lateral deflection decreased at higher height of non-yielding retaining wall.

**Figure 4.18:** Effect of Wall Inclination Angle, $\omega$, on the Location of the Horizontal Earth Force Resultant
Figure 4.19: Effect of Wall Height on Normalized Wall Lateral Deflection and Normalized Lateral Earth Pressure

Figure 4.19b illustrates the effect of the model wall height on the lateral earth pressure exerted on back of the wall. This figure indicates that both the trend and the normalized lateral earth pressure are similar for walls with different heights, especially at the top half of the wall. At the bottom half of the wall, the trends are similar; however, there is a slight increase in the value of lateral earth pressure for the short walls compared to the long. Figure 4.19b also shows that the predicted values using Jaky’s formula significantly under-estimated the values calculated by the numerical approach. The values calculated by Mayne and Kulhawy are closer to the numerically-predicted values.

Figure 4.20 summarizes the vertical and horizontal earth forces of the non-yielding retaining walls at different wall heights. As the wall height increased, the normalized earth force seemed to decreased slightly. The value of the normalized horizontal earth
force approached the value predicted by Mayne and Kulhawy when the wall height was $H = 10$ m. However, the numerical values are still much higher compared to the values predicted by Jaky. The figure also showed that the wall height, $H$, has no effect on the normalized vertical earth force measured at the wall footing. However, for all wall heights inspected in the current investigation, the vertical earth forces are always larger the wall-self weight, $W_w$. This is attributed to the down drag forces developed at the back of the wall due to the wall lateral deflection.

![Figure 4.20: Effect of Wall Height on Normalized Vertical and Horizontal Earth Forces](image)

Figure 4.20 shows the numerically-measured and theoretically-predicted resultant elevations ($y_R$) above the wall footing normalized to the wall height, $H$. As mentioned before, an increase in the non-yielding wall height reduces the value of the lateral earth force at the bottom half of the wall (Figure 4.19b). Therefore, the location of the resultant lateral force dragged slightly towards the top of the wall as the wall height increased. However, the location stays around the $H/2$ value for all different wall heights. It can be concluded that the $H/3$ value assumed by theoretical formulas under-estimates the location of the lateral earth force, $y_R$. 

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4.8 Conclusion

In this chapter, the numerical model presented in Chapter 3 was used to study the geometry as well as material property effect on the static behaviour of a non-yielding retaining wall. The parameters of non-yielding walls examined are divided into two categories. The first category includes material properties of the wall-soil system such as the backfill soil friction angle ($\phi$), wall panel elasticity ($E_s$), degree of consolidation of sand backfill ($OCR$), and wall-soil interface friction angle ($\delta$). The second category includes the geometrical properties of the wall such as wall height ($H$) and wall inclination ($\omega$). Based on the results presented in this chapter, the following points can be summarized:

- Increasing the friction angle of the backfill soil, wall elastic modulus, and inclination of the wall panel led to a decrease in the wall lateral deflection. On the other hand, wall lateral deflection increased with the backfill soil degree of
consolidation and height of the wall. Finally, the wall-soil interface friction angle showed an insignificant effect on the wall lateral deflection.

- Increasing the friction angle of the backfill soil and wall panel inclination angle reduced the horizontal earth pressure exerted on the back of the wall. However, increasing the degree of consolidation of backfill soil increased the lateral earth pressure. Moreover, no significant effects were noticed on the lateral earth pressure due to the wall elastic modulus, wall-soil interface friction angle, or wall height. For all different parameters investigated in this study, lateral earth pressure on the wall was under-predicted by Jaky’s and Mayne and Kulhawy’s formulas.

- Increasing the friction angle of the backfill soil, inclination of wall panel, and wall height resulted in a reduction of the lateral earth force. In addition, increasing the values of the degree of consolidation and the elasticity of the facing panel exerted more lateral earth force on the back of the wall. However, a change in the values of the wall-soil interface friction angle did not have a significant effect on the horizontal earth force.

- All model walls tested in this study indicated vertical forces at the base larger than the wall-self weight. The only exceptions to this observation were the walls with non-vertical wall panels (i.e., inclined walls with \( \omega = 15^\circ \)). In this specific wall, the vertical earth force becomes less than the self-weight of the wall.

- The elevation of the resultant lateral force above the base increased when the friction angle of the backfill soil increased. On the other hand, increasing the degree of consolidation of the backfill soil and the elastic modulus of wall panel lowered the location of the resultant force towards the base. However, changes in the wall-soil interface friction angle, wall angle of inclination, and wall height showed an insignificant influence on the location of the resultant lateral force. It should be noted that in all the models, the Jaky and Mayne and Kulhawy formulas under-predicted the location of the resultant lateral force.
Chapter 5: DYNAMIC RESPONSES OF NON-YIELDING RETAINING WALLS

5.1 Introduction

In this chapter, the calibrated numerical model developed in Chapter 3 is used to carry out a parametric study to investigate the effect of different material parameters on the dynamic behavior of a non-yielding retaining wall. Metrical properties such as soil bulk and shear modulus, soil friction angle, wall elastic modulus, and other properties are changed to observe the interactive effect of these design factors on the wall seismic responses. The material properties examined in this section include:

- Backfill soil friction angle ($\phi$)
- Degree of consolidation of sand backfill ($OCR$)
- Facing panel elasticity ($E_s$)

The dynamic effect of each of these material properties on wall lateral deformation, lateral earth pressure, lateral earth force, vertical facing panel load, and lateral force resultant location is studied through 14 seconds of real base excitation to the foundation of a non-yielding wall. It should be noted that horizontal seismic base excitation has dominant influence on the behavior of a non-yielding retaining wall. Therefore, only the effect of horizontal seismic base excitation is considered in this study (i.e., $k_v = 0$). All the model walls are constructed on a firm foundation with a vertical rigid facing panel and horizontal backfill surface (i.e., $\beta = 0$). For each model wall, both top and bottom vertical loads, $R_{VT}$ and $R_{VB}$, are directly recorded during the numerical analysis. In addition, top and bottom horizontal loads ($R_{HT}$ and $R_{HB}$) are measured. The total lateral earth force, $R_H$, vertical force, $R_V$, and earth pressure resultant point of application, $y_R$, are calculated according to Equations 4.1 to 4.3 and Figure 4.1 presented in Chapter 4.
5.2 Effect of Backfill Soil Friction Angle (ϕ)

5.2.1 Wall Lateral Deformation

To study the effect of the backfill soil friction angle (ϕ) on the response of the non-yielding wall, five different granular soils were chosen as the backfill materials. The values of the soil friction angle (ϕ) ranged from 30º to 50º with 5º increments. These values of friction angles can be argued to represent the full range of sandy soil. Figure 5.1 shows the effect of the backfill soil friction angle on the time history of the lateral deformation of the non-yielding retaining wall for the full 14 seconds of the base excitation. In order to get the absolute wall lateral deflection, the input base displacement is subtracted from the total displacement of the wall at each height, and maximum lateral displacement (Δx) is normalized to the wall height, H, for each model wall. Therefore, all displacement-related curves discussed in this chapter represent only the dynamic deflection increment above the static values which were discussed earlier in Chapter 4.

The maximum and minimum values of the horizontal deformation of the retaining wall happen to be in the interval of 3.5 to 4.5 seconds from the beginning of the base shaking. This is expected as this time interval contains the maximum and minimum values of input base acceleration. Despite the change in rigidity of the wall-soil system by changing the internal soil friction angle, deflection of all walls followed the same trend of change with time.
Figure 5.1: Time Histories for Wall Lateral Deflection at Mid-Height with Different Backfill Soil Friction Angles
Figure 5.2: One-Second Window of Maximum Lateral Displacement of Model Wall and Input Base Acceleration (Hatched Area in Figure 5.1)
Figure 5.2 represents a one-second time interval between 3.5 to 4.5 seconds where the maximum and minimum values of deformation occur. In other words, this figure is snapshot of the hatched area in Figure 5.1. It should be noted that the maximum positive deflection occurs at the maximum negative acceleration and vice versa. Therefore, the maximum positive deflection should coincide with the maximum negative acceleration. However, Figure 5.2 shows different results, as the maximum positive deflection lags behind the maximum negative acceleration by about a 0.06 second interval. This means that the wall deflection lags behind the input base acceleration by about $\pi/3$. This conclusion is true for all friction angle values used in the current investigation. In addition, this time lag is due to the travelling velocity of the waves from the bottom the wall to the mid-height where the maximum deflection is recorded. This velocity, according to the theory of wave propagation into the soil mass, is not affected by the soil friction angle. Instead it is significantly affected by the shear modulus and damping of soil. In all models studied in this section, the shear modulus and damping are kept constant, and the soil friction angle was the only variable parameter [54].

Figure 5.3 shows the maximum and residual deformation values of the model wall due to changes in the friction angle of the backfill soil. It should be noted that values of lateral deflection shown in Figure 5.3 are the dynamic increment, $\Delta x_d$, which is caused by base shaking. The figure shows that the maximum and residual dynamic deflection increment increased as the friction angle increased. This result is unexpected since larger friction angles bring more resistance to mobilize soil shear and create less deflection of the retaining wall. However, this result can be interpreted in terms of the acceleration response of the model wall. Figure 5.4 shows the response acceleration at the wall mid-height for three walls constructed with different backfill soil friction angles. The figure clearly indicates that the input base acceleration amplitudes became greater as the waves traveled towards the top of the wall. At the same time there is a time lag between the response acceleration and input base acceleration. The response acceleration amplitude increased with the friction angle. However, the time lag does not show a significant change with the friction angle.
Figure 5.3: Variation of Maximum and Residual Dynamic Lateral Deflection of Wall with Backfill Soil Friction Angle

Figure 5.5 presents the variation of acceleration amplification factors at the mid-height of the wall panel and soil backfill with the backfill soil friction angle. The amplification factor is defined as the ratio of the response acceleration to input base acceleration amplitudes. It is clear that the acceleration amplification factor increased as the friction angle increased. According to the single degree of freedom (SDOF) analogy, the response ratio, $R$ (i.e., the ratio between the acceleration amplitudes at the mid-height and bottom of each model) can be calculated as follows [73]:

$$ R = \frac{1 + (2ξξ)²}{(1 - r²)² + (2ξξ)²} $$

(5.1)

where $ξ$ is the damping ratio, $r = \frac{f}{f_n}$ is the frequency ratio, $f$ is the input motion predominant frequency, and $f_n$ is the model wall fundamental frequency. According to SDOF analysis, the response ratio $R$ calculated from Equation 5.1 increased with an increasing frequency ratio ($r$) and with a decreasing damping ratio, $ξ$. It is strongly
believed that more experimental tests are needed to investigate the contribution of the friction angle ($\phi$) in both damping ratio, $\zeta$, and the model wall fundamental frequency, $f_n$. This figure (Figure 5.5) explains why the wall lateral deflection increased as the friction angle increased. This is attributed to the larger acceleration amplification associated with the backfill soil with a larger friction angle.

**Figure 5.4:** Response and Base Acceleration at Wall Mid-Height for Walls Constructed with Different Backfill Soil Friction Angles

**Figure 5.5:** Acceleration Amplification Factors at Wall Mid-Height for Walls Constructed with Different Backfill Soil Friction Angles
5.2.2 Lateral Earth Pressure

In order to check the variation of lateral earth pressure on the model wall height, ten different nodes along the back of the wall were selected to record the lateral earth pressure during seismic analysis. Among these 10 nodes, node 6 was located 0.5 m from the bottom, node 15 was located at mid-height, and node 24 was located 0.5 m from the top of the wall. Those nodes were chosen to represent the values of lateral earth pressure at the bottom, middle, and top of the wall, respectively.

Time histories for lateral earth pressure recorded at the bottom, mid-height, and top for walls constructed with backfill soil that had different friction angles are shown in Figures 5.6, 5.7, and 5.8. As expected, the transient value of lateral earth pressure at all nodes on the wall occurs in time interval of 3.5 and 4.5 seconds for different friction angles. This is the time interval where the few pulses of larger peak ground acceleration (PGA) occurred. In addition, this transient value increased as the PGA increased. The lateral earth pressure at the top and bottom nodes (top $0.25H$ and bottom $0.25H$) decreased with continuous shaking until it reached a residual value which, in general, was less than the static values (i.e., values at $t = 0.0 \text{ sec}$), see Figures 5.6 and 5.8. In contrast, the earth pressure at the middle of the wall (i.e., middle $0.5H$) increased significantly above the static values (Figure 5.7). The amount of increase in lateral earth pressure due to base shaking was less for higher soil friction angles. It is worth noting that the amplitude of lateral earth pressure is largest at the top of the wall (Figure 5.8), which may be due to the acceleration amplification explained earlier. Taken together, the results in Figures 5.6, 5.7, and 5.8 collectively indicated that the earth pressure at the back of the wall is redistributed towards the wall’s mid-height during base shaking.
Figure 5.6: Time Histories of Lateral Earth Pressure at the Bottom of Walls Constructed with Different Soil Friction Angles
Figure 5.7: Time Histories of Lateral Earth Pressure at the Mid-Height of Walls Constructed with Different Soil Friction Angles
Figure 5.8: Time Histories of Lateral Earth Pressure at the Top of Walls Constructed with Different Soil Friction Angles
Figure 5.9 shows a one-second window of the lateral earth pressure at the wall’s mid-height for walls constructed with different soil friction angles. It is clear from the figure that there is a phase shift between the input base acceleration and the response lateral earth pressure. In other words, the response lateral earth pressure lagged behind the input base acceleration by about 0.13 seconds. This is the time taken by the waves to travel up to the soil mid-height. This time is almost twice the time taken by the waves to travel up to the wall mid-height (Figure 5.2). This is logical as the shear modulus of the wall is significantly larger than the soil shear modulus, and therefore the wave velocity in the wall is expected to be much larger compared to the soil. This result concluded that the wall deflection precedes the lateral earth pressure by about 0.087 seconds. In other words, wall deflection and lateral earth pressure are not in phase.
Figure 5.9: One-Second Window out of Time Histories of Lateral Earth Pressure at Mid-Height of Walls Constructed with Different Soil Friction Angles (Hatched Area in Figure 5.7)
Figure 5.10 displays the variation of the maximum and residual earth pressure distributions on non-yielding walls constructed with different friction angles of backfill soil. The residual values were calculated at each elevation by taking the average reading of the last second of the lateral earth pressure time history recorded at each location (i.e., the 14th second in Figures 5.6, 5.7, and 5.8). However, the maximum lateral earth pressure represents the maximum transient value during base shaking, and is deduced from similar figures. Examples of maximum and residual points are shown in Figure 5.8f. Shown also in Figure 5.10 are the variations of static lateral earth pressure for the same model walls with the same backfill soil friction angles. Figure 5.10b indicates that during base shaking of the non-yielding wall, the lateral earth pressure increased beyond the static value at all locations of the wall height. However, the dynamic lateral earth pressure was more pronounced at the top half of the wall compared to the bottom half. In addition, Figure 5.10b indicates that the backfill soil with a higher friction angle imposed more lateral earth pressure at the top of the wall compared to the lower friction angle backfill. The opposite is true in the bottom of wall, where the backfill with the higher friction angle imposed a lower lateral earth pressure.

Figure 5.10a as expected proves that the backfill with a higher friction angle exerted lower residual earth pressure for the bottom 2/3 of the wall height. The opposite is true for the top 1/3 of the wall height, where higher friction angles produced higher residual earth pressure. For backfill soil friction angles $\phi = 50^\circ$, the lateral earth pressure returned back to its original static distribution (i.e., the distribution before base shaking) once the base shaking ceased. The residual earth pressure distributions, for lower friction angles, are considerably larger than the static value at the bottom 0.5H of the wall. However, the lateral earth pressure distributions were significantly lower than the static values at the top half of the wall. In conclusion, during base shaking, the top half of the non-yielding wall attracted more lateral earth pressure; however, the lateral earth pressure was redistributed towards the bottom half as the base shaking ceased.
5.2.3 Lateral Earth Forces

The horizontal earth forces developed at the top and bottom of non-yielding walls are of major interest to the design engineers. These forces will be transferred to either building foundations as horizontal forces or to the associated floor slabs as axial compressive forces. In both cases, the design engineer should be aware of these forces and their magnitudes to have a safe design. During numerical simulation, the horizontal reaction forces at the top and bottom of the non-yielding wall were recorded in both static and dynamic conditions. Effects of the backfill soil friction angle on the top, bottom and total horizontal reaction forces are shown in Figures 5.11, 5.12, and 5.13, respectively. The total horizontal reaction forces for each backfill soil friction angle, shown in Figure 5.10, illustrate the variation of lateral earth pressure with wall heights at different backfill soil friction angles.

**Figure 5.10:** Effect of Backfill Soil Friction Angle on the Variation of Lateral Earth Pressure with Wall Heights at Different Backfill Soil Friction Angles
5.13, is the summation of the horizontal reaction forces at the top (Figure 5.11) and at the bottom (Figure 5.12).

Figure 5.11 clearly indicates that the transient dynamic horizontal reaction at the top of the wall increased significantly above the static value. The dynamic horizontal earth force increment was larger for higher backfill soil friction angles (i.e. $\phi = 50^\circ$) compared to lower friction angles (i.e. $\phi = 30^\circ$). This conclusion could be attributed to the motion amplification associated with higher friction angles, which was explained earlier in Section 5.2.1 and shown in Figure 5.5. The wall constructed with backfill soil that has a higher friction angle showed larger acceleration amplification at the top of the wall. This motion amplification imposed more lateral earth pressure at the top of the wall, and as a result, more horizontal earth force reaction developed at the top. On the other hand, as the base shaking ceased, the horizontal reaction at the top of the wall approached the static values for higher friction angles (i.e. $\phi = 40^\circ$ to $50^\circ$). However, for smaller friction angles (i.e. $\phi = 30^\circ$ and $35^\circ$) the horizontal earth force at the top approached values lower than the static values at the end of base excitation. Similar conclusions could be summarized for the horizontal reaction forces at the bottom of the wall (Figure 5.12). The dynamic increment is slightly larger for higher friction angles than for lower friction angles. In addition, for all friction angles tested in the current investigation, the horizontal reaction at the bottom of the wall reached its static value once the input base excitation stopped.
Figure 5.11: Effect of Backfill Soil Friction Angle on Horizontal Reaction Force at Top of Non-Yielding Wall
Figure 5.12: Effect of Backfill Soil Friction Angle on Horizontal Reaction Force at Bottom of Non-Yielding Wall
Figure 5.13: Effect of Backfill Soil Friction Angle on Total Horizontal Reaction Force of Non-Yielding Wall
Figure 5.13 shows the effect of friction angle on total horizontal force. It can be concluded that, despite the slightly larger dynamic horizontal earth force increment developed for the larger friction angle, the total lateral earth force is still less compared to the wall constructed with a lower friction angle backfill. This is attributed to the larger soil shear strength that could be mobilized within the backfill soil with higher friction angles. In general, the aftershock values of the total horizontal earth forces approached the static values. The only exception is the wall constructed with a friction angle of $\phi = 30^\circ$, where the aftershock value of lateral earth force approached a value slightly less than the static value.

Figure 5.14 represents a one-second time interval between 3.4 to 4.4 seconds where the maximum top, bottom, and total horizontal earth forces are located in different backfill soil friction angles. It should be noted that the maximum positive lateral earth forces occurred at the maximum negative acceleration and vice versa. Figure 5.14 shows that the top, bottom, and total horizontal earth forces are all in-phase. However, these forces lag behind the maximum negative acceleration by about a 0.13 second interval. This means that the input base acceleration preceded the horizontal earth forces by about $2\pi/3$. This conclusion is true for all friction angle values used in the current investigation. It should be noted that this time lag is due to the travelling velocity of the waves from the bottom of the wall to the top where the top horizontal reaction force occurred. This velocity is not affected by the soil friction angle, and is only affected by the shear modulus and damping of soil. In all walls studied in this section, the shear modulus and damping ratio are kept constant, and the only parameter changed is the soil friction angle, $\phi$. 
Figure 5.14: One-Second Window out of Time Histories of Lateral Earth Forces at the Top and Bottom of Walls Constructed with Different Soil Friction Angles
Figure 5.15 shows the variation of the horizontal reaction at the top and bottom of non-yielding walls with different backfill soil friction angles. At each of the two locations (i.e., top and bottom), the maximum, minimum, and residual horizontal reactions are measured. In addition, the static values recorded at the top and the bottom are also shown in Figure 5.15 for the sake of comparison. It can be seen from Figures 5.15 that the horizontal reaction forces recorded at the bottom of the wall, $R_{HB}$, consistently decrease as the friction angle increases for the maximum, minimum and residual horizontal forces measured at the bottom of the wall, $R_{HB}$. The difference between the maximum and minimum horizontal forces recorded at the bottom is approximately constant at different friction angles. This means that the amplitude of the dynamic horizontal force response is not affected by the backfill soil friction angle. It can also be seen that the difference between maximum and residual horizontal bottom forces is approximately constant regardless of the friction angle value. This is an indication that the dynamic horizontal force increment is almost similar for all friction angle values used in the current study. Finally, for all friction angle values, the residual horizontal earth force at bottom of the wall approached the static value at the end of shaking.

![Figure 5.15: Maximum, Minimum, and Residual Horizontal Reaction Forces at the Top and Bottom of Walls Constructed with Different Friction Angles Backfills](image-url)
Regarding the horizontal reaction recorded at the top of the wall, $R_{HT}$, Figure 5.15 shows a negligible effect of the friction angle on the maximum and residual $R_{HT}$. In addition, the dynamic horizontal load increment measured at the top of the wall is approximately constant for different values of backfill soil friction angle. This is shown by the constant difference between the maximum and residual top horizontal forces. It can also be seen from Figure 5.15 that the residual value of $R_{HT}$ was slightly less than the static value for friction angles $\phi < 45^\circ$, and approached the static values thereafter (i.e., $\phi > 45^\circ$).

![Graph showing variations of total horizontal earth forces with different friction angles](image)

**Figure 5.16:** Maximum, Minimum, and Residual Total Horizontal Earth Forces for Walls Constructed with Different Friction Angle Backfills

Variations of the total horizontal earth forces with different backfill soil friction angles are shown in Figure 5.16. These values are calculated from Figure 5.15 by summation of $R_{HT}$ and $R_{HB}$ for maximum, minimum, and residual total horizontal earth forces. It should be noted that these values are equivalent to the total maximum, minimum, and residual lateral earth forces acting at the back of the wall. The figure
clearly indicates that the total lateral earth forces (i.e., maximum, minimum, and residual forces) decreased significantly with the increase of the backfill soil friction angle. It also can be seen that the difference between the maximum and minimum horizontal earth forces, which represent the dynamic amplitude, slightly increased with the friction angle. In addition, the difference between the maximum and residual horizontal earth forces, which represents the dynamic horizontal earth force increment, is approximately constant with the friction angle. Finally, the value of residual horizontal earth forces approached the static values at all friction angles used in this study.

5.2.4 Vertical Earth Forces

Figure 5.17 shows the effect of the backfill soil friction angle, $\phi$, on the total vertical load developed at the bottom of non-yielding walls constructed with different backfill soils (i.e., different friction angle). It can be noticed from the figure that the friction angle has a slight effect on the time response of the vertical reaction at the bottom of the wall. In addition, the residual vertical force after the input base shaking ceased approached values which are less than the static values. Finally, the dynamic vertical force increment above the static value decreased as the friction angle increased.
Figure 5.17: Effect of Backfill Soil Friction Angle on Total Vertical Reaction Force at the Bottom of a Non-Yielding Wall
Figure 5.18 illustrates the residual, minimum, and maximum values of vertical load developed at the bottom of the wall constructed with different backfill soil friction angles. Generally, the maximum vertical force slightly decreased and the minimum vertical force slightly increased with the increase of the backfill soil friction angle. However, the residual vertical forces do not show any change with the friction angle. The difference between the maximum and minimum vertical forces, which represent the dynamic amplitude, is slightly decreased as the friction angle increased. Similarly, the difference between the maximum and static vertical force, which represents the dynamic vertical force increment, is also decreased as the friction angle increased. Finally, the residual vertical forces (i.e., forces after the base shaking ceased) approached values significantly less than the static values. However, both values, static and residual, are still larger than the wall self-weight, $W_w$.

Figure 5.18: Variation of Residual, Minimum, and Maximum Values of Vertical Load at Bottom of Wall Panel with Different Friction Angles
5.2.5 Lateral Earth Force Location

Figure 5.19 illustrates the variation of minimum, maximum, and residual lateral earth force locations on the back of the model wall with the backfill soil friction angle. The location of the lateral forces together with the force magnitudes are needed in order to calculate the bending moment on the wall in order to design the wall structurally. The figure clearly shows that the backfill soil friction angle has a significant effect on the lateral earth force location. As the friction angle increased, the maximum lateral earth force location moves upward from almost $0.4H$ at $\phi = 30^\circ$ to above $0.5H$ at $\phi = 50^\circ$. However, the minimum lateral earth forces move downward as low as $0.3H$ for all friction angles used in the current study. It should be noted that the locating the lateral earth force at or closer to $0.5H$ is expected to produce the largest bending moment on the wall panel. As a general conclusion, the location of the maximum dynamic lateral force is approximately $0.05H$ above the location of the static lateral forces at the same friction angle. Finally, the location of the residual lateral forces is shown to be slightly below the location of the static lateral forces for the same friction angle.

![Figure 5.19: Variation of Minimum, Maximum, and Residual Lateral Earth Force Location with Different Backfill Soil Friction Angles](image_url)
5.3 Effect of Backfill Soil Over-Consolidation Ratio (OCR)

In order to study the effect of backfill soil degree of consolidation on the response of non-yielding retaining walls, backfill soils with different degrees of consolidation were used in the numerical simulation. Backfill soil with a degree of consolidation (OCR) equal to 1, 2, 3 and 4 were selected for the current investigation. Results were compared in terms of lateral deflection on the wall’s mid-height, earth pressure distribution through the wall height, lateral earth force at the wall boundaries, vertical earth force at the wall foundation, and location of the lateral earth force at the back of the wall. Variations of those responses under base excitation are presented in this section.

5.3.1 Wall Lateral Deformation

Figure 5.20 shows the variation of the maximum and residual dynamic deflection increments at the mid-height of the wall, due to base shaking, with the backfill soil degree of consolidation. The dynamic deflection increment is the lateral deflection occurring due to the input base excitation above the static deflection covered in Chapter 4. Figure 5.20 clearly indicates that the wall lateral deflection decreased as the backfill soil degree of consolidation increased. In other words, compacting the soil backfill resulted in a larger over-consolidation of the soil and therefore a reduction of the lateral deflection of the non-yielding wall. The effect of the degree of consolidation on the residual deflection is more pronounced compared to the maximum deflection. In other words, the effect of backfill soil degree of consolidation on the maximum dynamic deflection increment is less significant compared to the residual deflection increment. Figure 5.20 also shows that the effect of the degree of consolidation on maximum and residual lateral deflection becomes less significant after OCR = 3. This means that as the over consolidation ratio increased beyond OCR = 3, the reduction on the wall lateral deflection became less important. In conclusion, there was a major residual deflection after dynamic excitation stopped, and this residual deflection was larger for the backfill soil with smaller degrees of consolidation.
Figure 5.20: Maximum and Residual Dynamic Deformation Increments of Model Wall Constructed with Backfill with Different Over-Consolidation Ratios

5.3.2 Lateral Earth Pressure

Figure 5.21 illustrates the residual and maximum earth pressure distribution at the back of non-yielding walls constructed with backfill soil having different over-consolidation ratios. Shown also in Figure 5.21 are static earth pressure distributions for the same walls used in dynamic analysis. For the maximum dynamic lateral earth pressure, Figure 5.21b, it can be concluded that the input base excitation developed significant dynamic lateral earth pressure increments above the static value at the top $0.5H$ of the wall. This is true for a backfill soil with an over-consolidation ratio of $OCR \leq 3$. For $OCR = 4$, the increase in the lateral earth pressure due to base acceleration is minor. The change in the lateral earth pressure due to input base acceleration is insignificant for the bottom $0.5H$ of the wall. Except for the backfill soil with $OCR = 4$, the increase in the lateral earth pressure at the top half of the wall is approximately comparable for all over consolidation ratios. This large increase in the earth pressure at the top half of the wall may be attributed to the acceleration amplification that was explained in the previous section.
For the residual lateral earth pressure, Figure 5.21a indicated that an increase in the earth pressure above the static value remains at the end of the dynamic excitation. This increase mainly occurred at the top half of the wall. It can also be seen that the residual lateral earth pressure distribution is almost the same for backfills with a degree of consolidation, $OCR = 1, 2, \text{ and } 3$.

5.3.3 Lateral Earth Forces

Figure 5.22 illustrates the effect of backfill soil degree of consolidation on the maximum, minimum, and residual horizontal load developed at the bottom ($R_{HB}$) and top ($R_{HT}$) of the model wall. The figure clearly indicates that the maximum, minimum, and residual horizontal force increased significantly with the backfill soil degree of consolidation. This is true for the horizontal forces measured at the top ($R_{HT}$) and at the
bottom ($R_{HB}$) of the wall. In addition, the measured horizontal load at the top was considerably larger compared to maximum, residual, and minimum values of bottom horizontal load. The effect of the over-consolidation ratio on the bottom lateral force is more pronounced compared to the top force. The difference between maximum and minimum values of the horizontal load measured at the top, which represent the dynamic amplitude, is significantly larger compared to the same difference for the bottom horizontal force. This large dynamic amplitude at the top can be attributed to the acceleration amplification at the top of the wall. Finally, the residual lateral force measured at the top is larger than the residual lateral force measured at the bottom of the wall.

![Graph showing the relationship between over-consolidation ratio and horizontal force](image)

**Figure 5.22:** Maximum, Minimum, and Residual Lateral Force at the Bottom and Top of Walls with Different Over-Consolidation Ratios

Figure 5.23 shows the relationship between over-consolidation ratios of backfill soil and the total horizontal load measured at the back of the wall. The total horizontal load is the summation of the load measured at the bottom and top of the wall during dynamic
base excitation (i.e., $R_H = R_{HB} + R_{HT}$). The figure clearly indicates that the over-consolidation ratio increased to maximum, minimum, and residual values of the lateral earth force at the back of the wall panel. However, the difference between maximum and minimum values, which represent the dynamic earth force amplitudes, is slightly affected by the backfill degree of consolidation. Moreover, the difference between the maximum lateral forces and static lateral forces shows a slight change with the soil degree of consolidation, which means that the lateral force dynamic incremental is slightly changed with the soil degree of consolidation. The most important result shown in Figure 5.23 is that the residual lateral forces are much larger than the static lateral force. This indicates that a significant value of dynamic lateral earth forces was retained in the soil-wall system after the base excitation stopped. The amount of dynamic lateral earth force increment retained by the soil-wall system after stopping the base excitation is larger for lower degrees of consolidation compared to higher degrees of consolidation.

![Figure 5.23: Maximum, Minimum, and Residual Total Lateral Force on Model Walls with Different Over-Consolidation Ratios](image)

Figure 5.23: Maximum, Minimum, and Residual Total Lateral Force on Model Walls with Different Over-Consolidation Ratios
5.3.4 Vertical Earth Forces

Figure 5.24 shows the variation of maximum, minimum, and residual values of vertical load exerted at the bottom of the model wall with different backfill soil over-consolidation ratios. Generally, the change in backfill soil over-consolidation does not have major effects on the vertical load and there is a slight increase in the maximum value and a slight decrease in the minimum value as the over-consolidation ratio of the backfill soil increased. However, the values of the maximum and minimum vertical forces for the wall constructed with backfill soil having an $OCR = 4$ do not follow the trend. For this model, the maximum transient value significantly increased and the minimum transient value significantly decreased. This dramatic change is believed to be a result of soil arching that might take action with the backfill soil with higher over-consolidation ratios. According to [12], arching becomes more pronounced as the soil backfill becomes denser, or heavily consolidated. It can be seen from Figure 5.24 that the residual values of the vertical earth force developed at the bottom of the wall are not affected by the backfill soil degree of consolidation. Nevertheless, these residual values are less than the statically-developed values, and still larger than the self-weight of the wall panel.

![Figure 5.24: Variation of Maximum, Minimum, and Residual Values of Vertical Earth Force with Different Over-Consolidation Ratios](image-url)
5.3.5 Lateral Earth Force Location

Figure 5.25 illustrates the effect of the backfill soil over-consolidation degree on the location of resultant lateral earth force. The figure indicates that as the over-consolidation ratio of the backfill increased, the dynamic resultant location above the base decreased. This is true for both the maximum and residual resultant locations. However, in the case of the minimum resultant location, the resultant location moves toward the bottom of the wall for models with over-consolidation ratios $OCR = 1$, 2, and 3. But, for walls with backfill soil that has an $OCR = 4$, the minimum resultant moves up slightly. It can be concluded that the transient earth force location could go as high as $y_R = 0.7H$ and as low as $y_R = 0$. For the residual earth force location, it can be seen that it is higher than the static earth force location, and it could go as high as $0.6H$ and as low as $0.5H$. It is important to note that earth force location is needed to calculate the wall maximum bending moment.

![Figure 5.25: Variation of Maximum, Minimum, and Residual Location of Resultant Earth Force with Backfill Soil Degree of Consolidation](image-url)
5.4 Effect of Wall Panel Modulus of Elasticity ($E_s$)

In order to study the effect of a non-yielding wall modulus of elasticity ($E_s$), three different values of the modulus of elasticity ($E_s$) were selected for the wall panel. The values selected for the modulus of elasticity represent wood material, low strength concrete, medium strength concrete and high strength concrete. In this section, the effect of the wall panel elastic modulus on wall lateral deflection, lateral earth pressure distribution on the back of the wall, lateral earth force magnitudes and locations, and vertical earth force developed at the base of the wall are studied. The dynamic response will be compared to the static response in order to identify the additional dynamic increment above the static value.

5.4.1 Wall Lateral Deformation

The dynamic displacement increment ($\Delta x_d$) normalized to the wall height $H$ is shown in Figure 5.26 for different wall modulus of elasticity. It is important to note that the reference model has a wall panel made of wood, which means that the modulus of elasticity for this model is almost 10 times less than the elasticity of the wall panel made of low strength concrete. Therefore, it is expected that the model with a wooden wall panel will develop a maximum lateral deflection almost 4 times larger than the model with a low strength concrete panel. Similarly, the residual lateral deflection of this model (i.e., a wood material wall) is almost 2 times larger compared to the concrete made wall panel. In case of model walls constructed with concrete panels, it can be seen that the strength of the concrete has a slight effect on both the maximum and residual dynamic deflection increment. For example, increasing the concrete strength from normal to high strength concrete resulted in a reduction in the wall maximum lateral deflection by about 20%. However, both walls with normal and high strength concrete showed almost zero residual lateral deflection at the end of an earthquake.
Figure 5.26: Variation of Maximum and Residual Wall Deflection with a Non-Yielding Wall Modulus of Elasticity

5.4.2 Lateral Earth Pressure

Figure 5.27 illustrates the residual and maximum earth pressure distribution at the back of non-yielding walls constructed with different wall panel modulus of elasticity ($E_s$). Shown also in Figure 5.27 are static earth pressure distributions for the same walls used in the dynamic analysis. Figure 5.27b, which shows the maximum dynamic lateral earth pressure, proves that the input base excitation developed a significant dynamic lateral earth pressure increment above the static value at different heights of the wall.
The increase in the maximum lateral earth pressure due to dynamic loading was more significant as the rigidity of the wall panel increased (i.e., as $E_s$ increased). In other words, the wall panels made of concrete developed dynamic lateral earth pressure, over the static value, much larger compared to the wall panel made of wood material. The maximum earth pressure value occurred at approximately $H/3$ from the top of the wall. For the model wall with wooden panels, the increase in the lateral earth pressure due to base acceleration was insignificant.

For the residual earth pressure shown in Figure 5.27a, the figure indicated that the residual lateral earth pressure distribution for walls made of concrete is approximately compatible with the static earth pressure distribution, both in shape and magnitude.
However, the wall with wood panels retained a residual lateral earth pressure larger than the static values at some locations, and less than the static values at other locations.

### 5.4.3 Lateral Earth Force

Figure 5.28 illustrates the effect of the wall panel modulus of elasticity ($E_s$) on the maximum, minimum, and residual horizontal load developed at the bottom ($R_{HB}$) and top ($R_{HT}$) of the model wall. The figure clearly indicates that the maximum horizontal force, at both the top and bottom of the wall, increased significantly with the wall modulus of elasticity. In contrast, the minimum lateral earth force, at both the top and bottom of the wall, did not show any change with the wall modulus of elasticity. The top reaction slightly decreased for residual lateral earth forces, while the bottom reaction slightly increased with the wall modulus of elasticity. In addition, the measured horizontal load at the top was significantly larger, compared to the bottom horizontal load, for the maximum and minimum values. The difference between the maximum and minimum values of the horizontal load measured at the top, which represent the dynamic amplitude, was significantly larger compared to the same difference for the bottom horizontal force. This large dynamic amplitude at the top could be attributed to the acceleration amplification at the top of the wall. This amplitude increased as the wall modulus of elasticity increased. The strength of concrete did not show a significant effect on lateral earth force measured at the top and the bottom of the wall. This final conclusion is true for maximum, minimum, and residual lateral earth forces.
Figure 5.29 shows the relationship between the wall elastic modulus and the total horizontal load measured at the back of the wall. The total horizontal load is the summation of the load measured at the bottom and the load measured at top of the wall during dynamic base excitation (i.e. $R_H = R_{HB} + R_{HT}$). The figure clearly indicates that maximum, minimum, and residual values of the lateral earth force at the back of the wall panel increased as the elastic modulus of the wall panel increased. The increase in the maximum lateral force was more pronounced compared to the increase in both minimum and residual forces. However, within the walls made of concrete panels, the effect of concrete strength in the lateral earth force was insignificant. The difference between maximum and minimum values, which represent the dynamic earth force amplitudes, increased with the wall elastic modulus. Moreover, the difference between the maximum lateral forces and static lateral forces, which represent the dynamic lateral load increment, shows an increase with wall elastic modulus. The most important result shown in Figure
5.29 is that the residual lateral forces are much larger than the static lateral force. This indicates that a significant value of dynamic lateral earth forces was retained in the soil-wall system after the base excitation stopped. The amount of dynamic lateral earth force increment retained by the soil-wall system was larger for walls with a lower elastic modulus.

![Figure 5.29: Maximum, Minimum, and Residual Total Lateral Force on Model Wall with Different Elastic Modulus](image)

**Figure 5.29:** Maximum, Minimum, and Residual Total Lateral Force on Model Wall with Different Elastic Modulus

### 5.4.4 Vertical Earth Forces

Figure 5.30 shows the variation of maximum, minimum, and residual values of vertical load exerted at the bottom of model wall with different elasticities. This figure clearly indicates that the residual values of $R_v$ are almost the same for all the models while the maximum values significantly decrease as the modulus of elasticity of the wall increases. For the case of minimum values, the trend is the other way around and it increases as elasticity increases. It can be seen from Figure 5.30 that the maximum, minimum, and residual values of the vertical earth force developed at the bottom of the
wall are not affected by the concrete strength. Nevertheless, these residual values are less than the statically developed values, and still larger than the self-weight of the wall panel.

![Graph showing vertical force vs modulus of elasticity](image)

**Figure 5.30:** Residual, Minimum, and Maximum Values of Vertical Load on Bottom of Facing Panel with Different Modulus of Elasticity

### 5.4.5 Lateral Earth Force Location

Figure 5.31 shows the effect of the wall panel elastic modulus on the location of the lateral earth force at the back of the model wall. The location of the maximum lateral earth force shows a slight decrease with the model wall modulus of elasticity. However, it is still close to 0.6H for all elastic modulus values used. For the minimum lateral force location, it shows slight increase as the modulus of elasticity of the wall increases. Both maximum and minimum locations indicate that the lateral earth force is moving to as high as 0.6H and to as low as 0.1H during base shaking. For the residual lateral earth force, Figure 5.31 indicates that it is always closer to 0.5H regardless of the value of the wall modulus of elasticity. Nevertheless, the location of residual lateral earth force is slightly above the static lateral earth force for all values of elastic modulus used in the current study.
Figure 5.31: Variation of Maximum, Minimum, and Residual Location of Resultant Earth Force with Wall Modulus of Elasticity

5.5 Conclusion

In this chapter the numerical model presented in Chapter 3 is used to investigate the influence of backfill soil friction angle, backfill soil degree of consolidation, and wall panel modulus of elasticity on the wall response due to base excitation using a real earthquake record. The reference wall in this numerical investigation was a low to medium height wall (i.e., $H = 4$ m) with a dry cohesionless granular soil, and a non-yielding rigid foundation. In this investigation, the walls were subjected to horizontal ground motion matching an actual scaled earthquake record. Based on the results presented in this chapter, the following points can be summarized:

- Increasing the internal friction angle of the backfill soil caused a motion amplification throughout the wall height, and therefore increased the maximum and residual dynamic deflection of the wall panel. However, these values decreased when the degree of consolidation of the backfill soil and the wall panel modulus of elasticity increased.
• Increasing the friction angle of the backfill soil consistently decreased the dynamic horizontal earth force at the bottom of the wall. However, it had an insignificant effect on the maximum and residual dynamic horizontal force at the top of the wall. In addition, as backfill soil friction angle becomes larger than 40°, the residual horizontal earth force becomes closer to the static force. On the other hand, increasing the backfill soil degree of consolidation and the wall panel modulus of elasticity caused a significant increase in the dynamic horizontal force at both the top and bottom of the wall.

• Vertical earth force was slightly affected by increasing the friction angle and degree of consolidation of backfill sand. In addition, residual vertical forces were less than static forces but higher than the self-weight of the model wall. However, increasing the elasticity of the model wall decreased the maximum vertical earth force. Moreover, in the case of wall elasticity, residual vertical force was less than static force.

• The location of maximum and residual dynamic lateral earth forces increased as high as 0.5H when the friction angle of the backfill soil increased. However, the minimum location of dynamic horizontal earth force can be as low as 0.3H. On the other hand, increasing the degree of consolidation of backfill sand lowered the location of the maximum and residual dynamic horizontal earth force. Nevertheless, the elasticity of the facing panel had an insignificant effect on the maximum and residual earth force locations.
Chapter 6: CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusion

The main objective of the current study was to investigate the static and dynamic response of a non-yielding wall retaining over-consolidated sandy soil. In order to meet this objective, a numerical model was developed using a dynamic finite difference program, FLAC [4] to simulate the measured dynamic and static responses of reduced-scale wall models. Then, the developed model was calibrated using experimental results [2, 3]. The calibrated numerical model was scaled to prototype size and used to carry out static and dynamic analyses of non-yielding retaining walls with different geometries and material properties. The effect of each parameter on the wall lateral deflection, lateral earth pressure and earth force, vertical earth force at the bottom of the wall, and location of the lateral earth force acting on the wall were investigated. These numerical results were compared with the current at-rest earth pressure theory and the major concluded points are summarized in this chapter.

6.1.1 Static Results

The parameters of non-yielding walls examined in this study are divided into two categories. The first category includes the material properties of the wall-soil system such as backfill soil friction angle ($\phi$), wall panel elasticity ($E_s$), degree of consolidation of sand backfill ($OCR$), and wall-soil interface friction angle ($\delta$). The second category includes the geometrical properties of the wall such as wall height ($H$) and wall inclination angle ($\omega$).

Backfill soil with a higher internal friction angle mobilized more shear strength. Therefore, increasing the friction angle of backfill soil resulted in less lateral deflection as well as less lateral earth pressure and force on the wall. However, the location of the resultant earth force moved up toward the top of the wall as the soil friction angle increased. Therefore, both Jaky’s and Mayne and Kulhawy’s theoretical methods under-predicted the location of the resultant force.

Increasing the degree of consolidation of the backfill soil caused exactly opposite of the results from friction angle analysis. As the compaction effort on the backfill soil
increased, lateral deflection of the wall as well as horizontal pressure and force exerted on the facing panel increased. However, having more degrees of consolidation for the backfill soil lowered the location of the resultant force. This reduction on the location of resultant force was more pronounced for higher values of OCR.

Regarding the wall panel elastic modulus, three different types of concrete were used to analyze the effect of this parameter on the static behavior of the retaining wall. It was realized that the wall lateral deflection decreased as the wall elastic modulus increased. However, it increased the lateral force exerted on the back of the wall panel. It should be noted that within the range of concrete modulus of elasticity, the change of this parameter did not have a significant influence on the lateral earth pressure and location of the resultant force.

The backfill soil-wall interface friction angle showed an insignificant effect on lateral deflection as well as lateral earth pressure and force. Moreover, the location of the resultant force did not change significantly for different interface friction angles and remained approximately constant. On the other hand, increasing the model wall inclination as well as wall height have the same results and both parameters resulted in a reduction in both lateral deflection and horizontal earth force. But, different angles of inclination did not have a major effect on lateral earth pressure distribution and location of resultant force.

6.1.2 Dynamic Results

The numerical model presented in Chapter 3 was used to investigate the influence of backfill soil friction angle, backfill soil degree of consolidation, and wall panel modulus of elasticity on the wall response due to base excitation using a real earthquake record. Results indicated that the backfill with a larger internal friction angle tended to amplify the input base acceleration and therefore imposed more dynamic and residual lateral deflection on the wall panel. In addition, as the friction angle of the backfill soil increased, the lateral earth force at the back of the wall panel consistently decreased. However, the backfill soil friction angle showed a slight effect on the vertical earth forces developed at the back of the wall panel as well as the location of the lateral earth force above the base.
The degree of consolidation for backfill soil as well as the elasticity of facing panel responses were similar for most of the cases. For example, the wall lateral deflection slightly decreased as OCR and $E_s$ increased. Similarly, the dynamic horizontal earth force at the back of the wall increased with the backfill soil degree of consolidation. Vertical earth force was slightly affected by the degree of consolidation of the backfill sand but slightly increased with the modulus of wall elasticity. Generally, the residual vertical forces developed at the bottom of the wall are less than the static values at most parameters investigated in this study. Increasing the degree of consolidation of the backfill sand and the wall modulus of elasticity slightly lowered the location of the maximum and residual horizontal earth force.

6.2 Recommendations

Backfill soil-wall interaction in the case of non-yielding retaining walls is very complicated. In order to resolve some of these complications, earth pressure distribution behind non-yielding retaining walls should be analyzed interactively with the lateral deflection of the wall. For simplicity, the current lateral earth pressure theory for at-rest conditions assumes a triangular earth pressure distribution with the resultant earth force located at $H/3$ ($H$ is height of the retaining wall). However, based on the results of the current study, this method needs more investigation. Below are recommendations for future study:

- A calibrated numerical model should be used to study the response of the prototype due to different earthquake records to identify the influence of input motion characteristics on the behaviour of non-yielding retaining walls.
- The effect of vertical input motion in combination with horizontal input motion should be investigated and compared to the results presented in this study.
- The effect of geometry and dimension on the dynamic response of the numerical model of non-yielding retaining walls should be investigated since it was out of the scope of this study.
- More experimental and numerical studies should be done for backfill soils with different moisture contents and different fin contents. In addition, this study can be done for sloped backfill soil.
• Finally, double-bay basements can be investigated with the numerical model developed in this study.
REFERENCES


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